AMC PAMPHLET

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QUALITY ASSURANCE

GUIDANCE TO NONDESTRUCTIVE TESTING TECHNIQUES

HEADQUARTERS, U.S. ARMY MATERIEL COMMAND

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FOREWORD

The Army Materiel Command (AMC) has an obligation to provide the Active Army with the finest, high quality products available. Such is our mission. It is our intent that through persistent efforts towards improvement and excellence at the Headquarters, subordinate commands, and all other levels, to achieve and maintain the highest possible standards of materiel quality in terms of effectiveness, reliability, and safe operations.

To attain these goals requires continuing awareness and utilization of the advancing technologies and techniques of quality assurance. This awareness and utilization is incumbent on all AMC personnel particularly those engaged in specifying or using quality, reliability, and maintainability control measures. Within these measures, the obvious advantages of nondestructive testing (NDT) and inspection methods make them most attractive as candidate materials, process, and product assurance controls. The NDT methods, in addition to being nondestructive, by definition, often readily lend themselves to 100 percent inspection requirements.

It is the considered intent of this handbook that, by providing a basic and broad overview of the more common methodologies constituting the field of NDT, AMC personnel may become more familiar with NDT test methods, applications, and the considerable advantages of specifying and using them.

An understanding of what NDT methods can accomplish can reasonably be expected to further motivate AMC specifiers and users of quality assurance measures, through broader utilization of NDT techniques, to expand and enhance their efforts in modernizing quality assurance operations, and in improving AMC materiel and overall quality assurance operations.

This document, then, is offered as a reference or guide to NDT methodologies. It is not intended that this document tell anyone how to perform a particular test or what tests to specify for a given application; these matters are necessarily the function of more specific or definitive documents such as specifications, engineering practices standards, TM's, TO's, TB's, WO's, and the like. The prime function of this document is to provide reference information on NDT methodologies in sufficient depth to foster an understanding and appreciation of what NDT can provide in the realm of product assurance.

Product Assurance requirements are specified by a variety of terms: quality and reliability assurance, producibility, maintainability, safety, and the like. Test methods to determine compliance with requirements are likewise variously classified, but, in general, they can be denoted as being either destructive or nondestructive in application. Destructive tests, by definition, impair the product being tested to an extent that prohibits the product being used for its intended purpose; nondestructive tests, also by definition, do not bar further use of the product. Thus, the principal advantage of NDT is obvious - acceptable products are not destroyed in their acceptance, and neither are unacceptable but repairable products.

The obvious question is -- what tests or group of tests constitute the field of NDT? However, there is a specific group of tests based on physical, chemical, and other scientific principles which most technical people agree pretty much covers the field of NDT as we know it today. All of these tests, in just about every application, satisfy the basic definition of a NDT. But, it is this acceptance by the technical community as being part of the NDT methodology that assures them the designation of an "NDT Method".

To many, NDT is an unfamiliar area in quality assurance, and one whose methods they hesitate to specify or use. They may not understand or appreciate the technologies and techniques involved, the pertinent and potential applications of the methods, the benefits and savings to be derived therefrom, and the criteria which can dictate specification or nonspecification of specific NDT methods, or NDT in general.

Such then is what this document will provide: information to those who are not familiar with NDT -- information of each of the several methodologies accepted today as constituting the technology of NDT. For each method, there will be given the scientific principles on which the method is predicated, the types of materials and item characteristics the method is generally used for, the equipment and standards normally associated with tests, method sensitivity, particular advantages and disadvantages, and any other information considered necessary to develop an understanding and appreciation of the NDT methods, and when and how such methods are used.

PART ONE

NONDESTRUCTIVE TESTING METHODS

Section I. INTRODUCTION

1. NONDESTRUCTIVE TESTING METHODS

By definition, a nondestructive test is any test which does not impair, damage, or otherwise affect the test object to an extent which would preclude further use of the object for its intended purpose. Obviously, any physical, chemical, mechanical, or other test method could, under the proper conditions, qualify as a nondestructive test. There is a spectrum of test methods, however, which are commonly recognized as being, and are specifically used as, nondestructive tests.

The following listing covers the NDT methods discuss this handbook. These methods are the more common of those generally gnized by both government and nongovernment activities as constituting the discipline of NDT.

1. Visual (including optical aids)
2. Liquid penetrant
3. Magnetic particle
4. X- and gamma-ray film radiography
5. Fluoroscopic and electronic X- and gamma-ray imaging systems
6. Sonic and ultrasonic
7. Eddy current
8. Conductivity (electromagnetic)
9. Microwave
10. Infrared
11. Liquid crystal
12. Kryptonation
13. Corona discharge
14. Leak testing

It can be seen that most of these methods involve energy forms associated with the electromagnetic spectrum (see Figure 1). The highlights and advantages/disadvantages of each of the methods will be discussed in detail in the following sections.

Section II. VISUAL INSPECTION

2. GENERAL

Visual inspection was probably the first, and is still the most basic and widely used NDT method. In visual inspection, the test item is observed

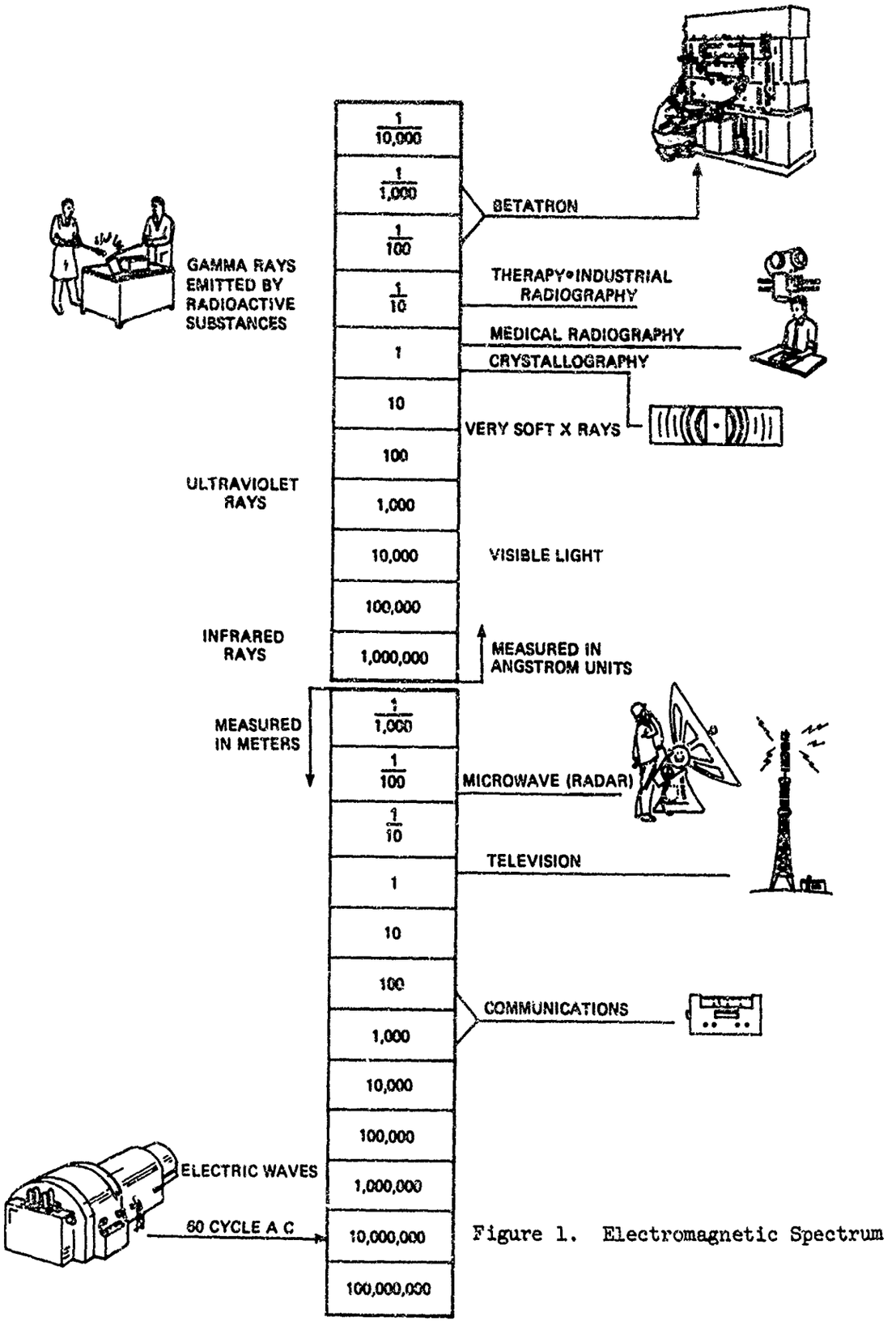


Figure 1. Electromagnetic Spectrum

directly, with reflected or transmitted radiation, or with the aid of such optical instruments as various types of magnifiers (including those with built-in illuminators and size scales), surface comparators, optical borescopes, etc. Borescopes are available, for example, which allow internal visual inspection of almost every critical portion of jet engines for high-performance aircraft. (See Figure 2.) One such borescope includes a self-contained camera adaptor which provides black and white or color photographs of the engine's interior. A closed circuit television viewing system is also provided for use with this device. Other visual inspection devices are used for examining the internal surfaces of gun barrels and the like.

The basic principle used in visual inspection is to illuminate the test item with light, usually in the visible region, and observe the surface for flaws. Inspection may involve illuminating the test item with infrared, visible, or ultraviolet radiation. The test item can be examined visually by the inspector or by use of light sensitive devices such as photocells. For example, pinholes in a metal strip can be detected by passing the strip between a light source and a photocell. When a pinhole passes the scanner, light shines through the hole into a detection chamber, causing the photocell to produce a signal that is amplified to operate a marker, alarm, or rejection mechanism.

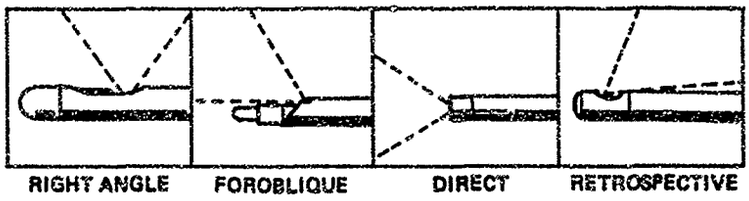
Visual inspection is usually simple, easy to apply, can be performed quickly, and is low in cost. In view of the advantages of this method, it should never be ignored — even when a test item is to be inspected using other NDT methods.

The results of visual examination may be of considerable assistance as a guide in other tests. For example, visual examination of a weld bead may aid in selecting the angle of incidence required for use in X-ray examination for cracks not visible at the surface. Also, visual examination of a completed weld by an experienced inspector can reveal a considerable amount of information about a weld, such as the presence of cracks, orientation and position of cracks relative to the various zones in the weld, surface porosity, unfilled craters, contour of the weld bead, presence of oxide film inclusions near the weld surface, undercutting, and potential sources of mechanical failure (such as sharp notches or misalignment).

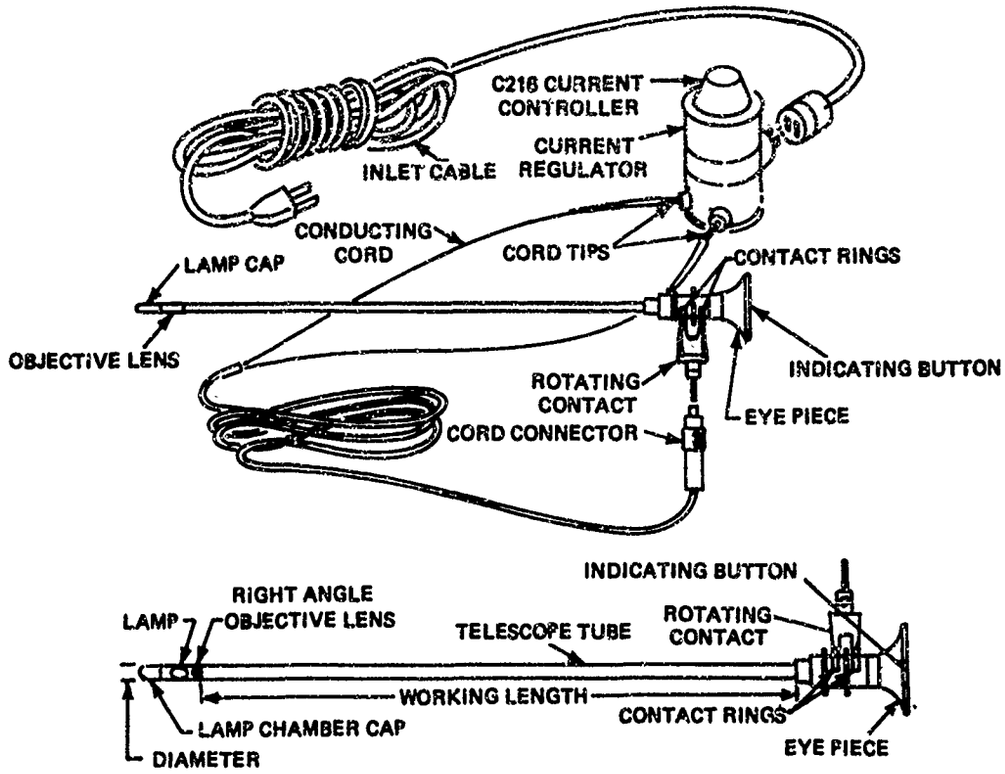
As in the case of all nondestructive tests, proper application of technique and equipment and correct interpretation of results are essential to reliability and effectiveness.

3. INSPECTION GUIDELINES

The surfaces of the test item should be adequately cleaned before inspection, e.g., sandblasting or shot blasting may be required. Such cleaning is especially important for heavy plate, for example, which often has adhering mill scale, scale pits, rough areas, and surface laps that can hide other flaws.



BORESCOPE ANGLES OF VIEW



NOMENCLATURE FOR RIGHT-ANGLE BORESCOPE

Figure 2. Optical Borescopes

A wide variety of possible visual inspection tasks may be performed. It is sometimes convenient to divide these into: (1) scanning tasks; (2) gaging tasks; and (3) monitoring tasks. Although there is always some difficulty in providing a classification scheme that will cover every case, the preceding classifications are helpful in providing a framework for discussion of inspection accuracy. These classifications are defined as follows:

Scanning -- The inspector searches for specified conditions by systematically examining the test item.

Gaging -- The inspector measures the dimensions of items using an instrument to determine if the measured dimensions are within tolerances.

Monitoring -- The inspector observes displays for indications of specified conditions. The inspector does not observe the material or product directly.

There are, of course, many ways to set up, perform, and document a repeatable and verifiable inspection. The main consideration here is to set up and organize such a program from the beginning to insure that documented and verifiable results are obtained from the inspections. In setting up a program for visual inspection, an example of a systematic approach is described here. The inspectors can be given a master list of reject conditions for a specific item to be inspected, and briefed regarding the type of flaws or unsatisfactory conditions expected. At selected times during the course of an inspection task, the results from a given number of inspections (a valid statistical sample) could be selected for an accuracy check. The results indicated by the various inspectors could be checked against results obtained by an experienced inspector using the same master list. Based on this comparison, inspection deficiencies and variations as well as other problem areas can be identified and corrected. Such an accuracy check can also be used to judge the adequacy of preinspection information available, inspection tools, aids, and techniques.

4. EQUIPMENT

a. General. A large number of optical aids are available to assist in visual inspection. Obviously, it is beyond the scope of this handbook to describe such equipment in detail. This would be both impractical and of limited value, since existing optical aids are continually being improved and other aids are being developed and marketed at a rapid rate. Detailed information is available on such devices from a variety of sources (including the manufacturers). However, some of the typical equipment will be covered here.

b. Optical Aids. Some typical optical aids are discussed in the following paragraphs.

(1) Magnifiers. Many magnifiers are available commercially ranging from low-power, wide-perspective instruments to those having a high

power or magnification and limited field of view. The major considerations in choosing a magnifier are: power (or magnification); working distance; field of view; chromatic correction; binocular or monocular vision; and resolving power (which may be defined as the extreme limit of fine structure clearly visible with a given instrument).

In using a magnifier to examine the surface of a large test item for defects, it is generally a good procedure to use a low-power magnifier, mark the questionable areas, then inspect the areas suspected of containing flaws with a high-power magnifier.

(2) Optical Microscopes. These are often used to detect and study fatigue cracks as follows: (a) determine the location of the first macroscopic crack in a test item where cracks are equally likely to occur at many places in the test item; (b) follow the course of the fatigue crack and determine the manner in which it is affected by grain boundaries, inclusions, and the like; and (c) study the development of microscopic cracks. The optical microscope is limited by the ability of the lens to resolve extremely fine detail. Sometimes it is desirable to examine flaws indicated by optical microscopes during NDT with an electron microscope, which is considered a laboratory instrument. The use of the electron microscope results in a manyfold increase in resolving power.

To enhance the use of the electron microscope, electron micrographs can be made from very thin plastic "castings" or replicas made by obtaining what is in effect a mold of the test item surface for detailed study of specific areas.

(3) Surface Comparators. The surface comparator provides a means for comparing a surface against a standard surface finish. The observer sees two surfaces side by side in a single field of view. It can show an ideal condition compared to the actual surface.

The comparator uses a small battery-operated light source, a semitransparent beam divider, and a magnifier. Part of the light goes to the reference surface and part of it goes to the test item surface. Flat and shiny surfaces reflect the filament image directly into the eye so that these parts look bright. Sloping or rough surfaces reflect the light so that these areas appear dark. Such illumination sharply differentiates surface pattern characteristics.

(4) Measuring Magnifier. The measuring magnifier combines a magnifier and a filar scale on the glass. The scale is set against the test item surface to permit measurement of small details on flat surfaces.

5. ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Equipment is usually low in cost.

(2) Tests are simple and easily applied.

(3) Many optical instruments are available for various types of inspection. (Some examples are mirrors, lenses, optical flats, microscopes, telescopes, and borescopes.)

(4) Certain detectors can convert infrared and ultraviolet radiation into visible light or electrical signals for subsequent interpretation.

(5) Remote viewing of test objects can be achieved with the use of television.

(6) The use of more than one wavelength of light will often give additional information.

b. Disadvantages.

(1) Inspection with visible light shows only surface conditions unless the object is made of a transparent material.

(2) Where fine detail is important, the examination of large surface areas can become a tedious task.

(3) Since surface conditions do not always reveal internal conditions, other studies, destructive or nondestructive, may be required to correlate surface and internal conditions.

(4) Resolution is limited by the wavelength of light used.

(5) The surface of the object must be clean, since surface coatings can hide defects.

(6) Defects may pass unnoticed where the object being inspected is large and must be viewed a portion at a time, or where defects are very small in comparison to the size of the item being inspected.

Section III. LIQUID PENETRANT INSPECTION

6. BACKGROUND

a. General Information. Liquid penetrant inspection can be performed on both nonmagnetic and ferromagnetic materials. Magnetic particle

inspection (see Section IV) can be performed only on ferromagnetic materials. Liquid penetrant nondestructive inspection generally consists of:

(1) Applying a penetrating liquid to the clean, dry surface of a test item.

(2) Removing the excess liquid from the exposed surface.

(3) Applying a porous developer which absorbs the liquid penetrant, thus giving an indication of test item surface flaws.

Penetrant inspection has been a widely accepted NDT method since the 1940's when modern type of penetrants were introduced. A forerunner technique known as the "Oil and Whiting Method" was used for over 50 years in the railroad industry. This older method consisted of using a high viscosity oil diluted with light oil such as kerosene to soak various parts such as crankshafts. The part was removed from the oil mixture, wiped clean, and coated with a whiting (chalk in denatured alcohol). The part was then vibrated with a pneumatic hammer to force the oil from flaws so that it would stain the whiting and thus provide indications of cracks. This method was never standardized and was replaced by better NDT methods when they became available.

b. Types of Penetrants. Penetrants may be classified into groups according to the type of dye used.

(1) Dye penetrants.

(2) Fluorescent penetrants.

Penetrants are also classifiable according to the manner of dye removal from the test item:

(1) Water washable.

(2) Solvent removable.

(3) Post emulsification (normally not water washable but made so by applying an emulsifier as an extra step after a suitable penetration time has been allowed).

c. Types of Developers. Two general types of developers are used in penetrant inspection. These are "dry" and "wet."

(1) Dry developers are generally used (in powder form) with fluorescent penetrants. The developing powder is applied after the penetrant has been applied and the test item surface rinsed free of surface (excess) penetrant and then dried. (The surface of the test part must be dry before the powder is applied or the powder will mat heavily in the liquid remaining on the part.) The test items can be dipped into a tank containing the

developer powder, or powder can be applied to large items using bulb or spray gun applicators. Excess powder may be gently blown off the test item with compressed air. A short time should be allowed for development of indications after the developing powder has been applied. This time should be in accordance with the penetrant manufacturer's instructions.

(2) Wet developers also may be used with fluorescent penetrants. These are applied to the surface of the test item after it is washed and before it is dried. Wet developers are generally supplied in the form of dry powders which are prepared for use by suspending them in a water bath. Parts being processed are dipped into this bath immediately after the washing operation and are then dried in a recirculating hot-air drier. The water from the wet developer is evaporated and a film of powder remains on the surface of the test item. Indications develop in a manner similar to those obtained through the use of dry developing powders. The developer should be tried out on an experimental basis before being used in actual testing. Cracking of the developer coating during the drying operation in the normal inspection procedure indicates:

(a) A serious loss of water.

(b) An excessive over-concentration of developer powder, which can obscure fine defects.

The wet developer generally used with the water-washable, fluorescent penetrant usually differs from that used with the post-emulsification type of penetrant. The recommended concentration of powder in the water suspension is also different, and the manufacturer's recommendations should be closely followed. The materials used in developers of the dry or water-suspension types are inert and noninjurious to most test items.

(c) Solvent-based developers. The developers used with portable visible-penetrant kits are solvent based. These developers are obtained in kit form. The powder developer is suspended in a liquid medium contained in an aerosol can. When solvent-based developers are stored, the solvents should be kept in closed containers to avoid contamination and evaporation, since the liquid suspending agent is usually volatile. If considerable amounts of liquid are lost through evaporation, the quality of the developer can be seriously degraded.

7. TEST CAPABILITIES

a. General. Liquid penetrant testing can be used to locate surface flaws in any nonporous material. Flaws such as surface cracks, porosity, and through leaks can be found in metals such as aluminum, magnesium, brass, copper, cast iron, stainless steel, titanium, as well as most alloys. Other materials that can be tested by this method include ceramics, plastics, molded rubber, and glass. Since some plastics and some rubber compositions are adversely affected by penetrants, sample tests should be performed before full scale tests are undertaken, so that material damage may be avoided. The manufacturer's recommendations should be followed.

b. Test Procedures and Guidelines. Appropriate cleaning before test is essential to liquid penetrant testing. The test item must be clean or the penetrant will not be effective. Also, after a test has been conducted, all of the penetrant residue must be removed or it may have a detrimental effect when the item is placed in service. Various types of cleaning for penetrant inspection purposes are discussed in the following paragraphs.

(1) Detergent cleaning. Immersion tanks and detergent solutions are commonly used in cleaning prior to penetrant inspection.

(2) Vapor degreasing. This process must be limited to use on those alloys and materials approved for this type of cleaning, since certain alloys can be structurally damaged by the process. It is useful for removal of oil products and similar organic materials. Tri- and perchloroethylene are often used for vapor degreasing.

(3) Steam cleaning. This process is useful for removing materials not easily removed by immersion cleaning.

(4) Solvent cleaning. This process is generally considered inferior to cleaning by use of detergents, steam cleaning, or vapor degreasing. Solvent cleaning may be performed using tanks or by applying it with a suitable applicator and wiping it off with a cloth or some other absorbent material.

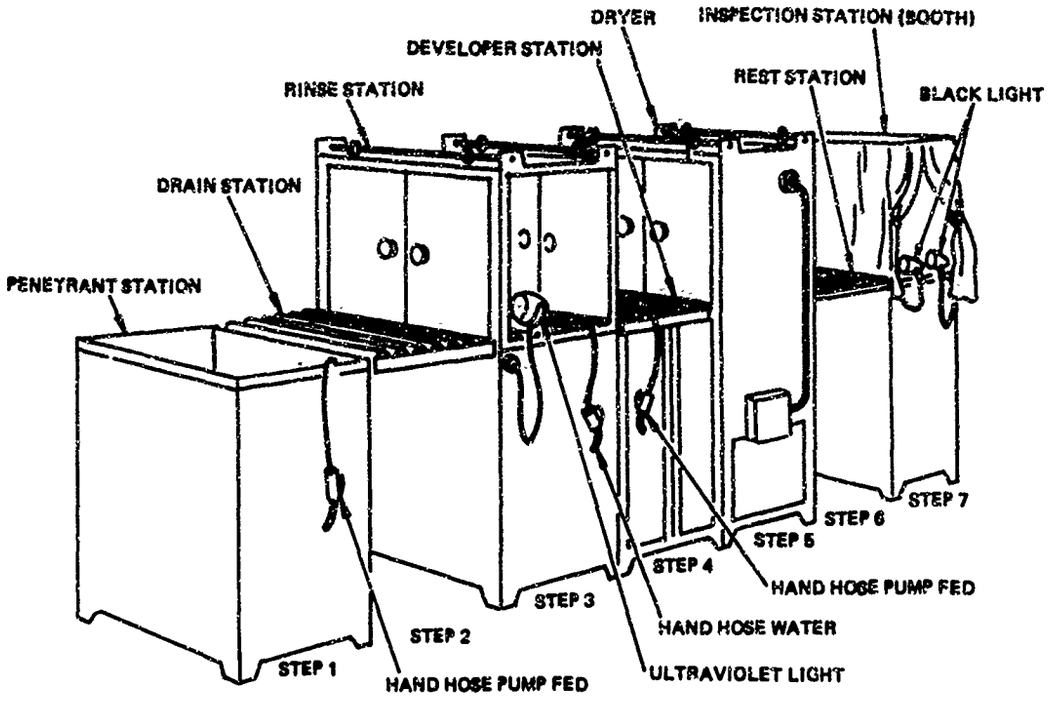
(5) Acid or alkaline cleaning. Such cleaning is used for removing rust and scale often present on test items after storage, pickling, etc. Suitable cleaning agents are commercially available for this process. The supplier's instructions should be followed in using such cleaners.

(6) Dissolving type, hot-tank paint strippers, bond release agents, and solvent paint strippers. These agents are also available commercially and the supplier's instructions should be followed.

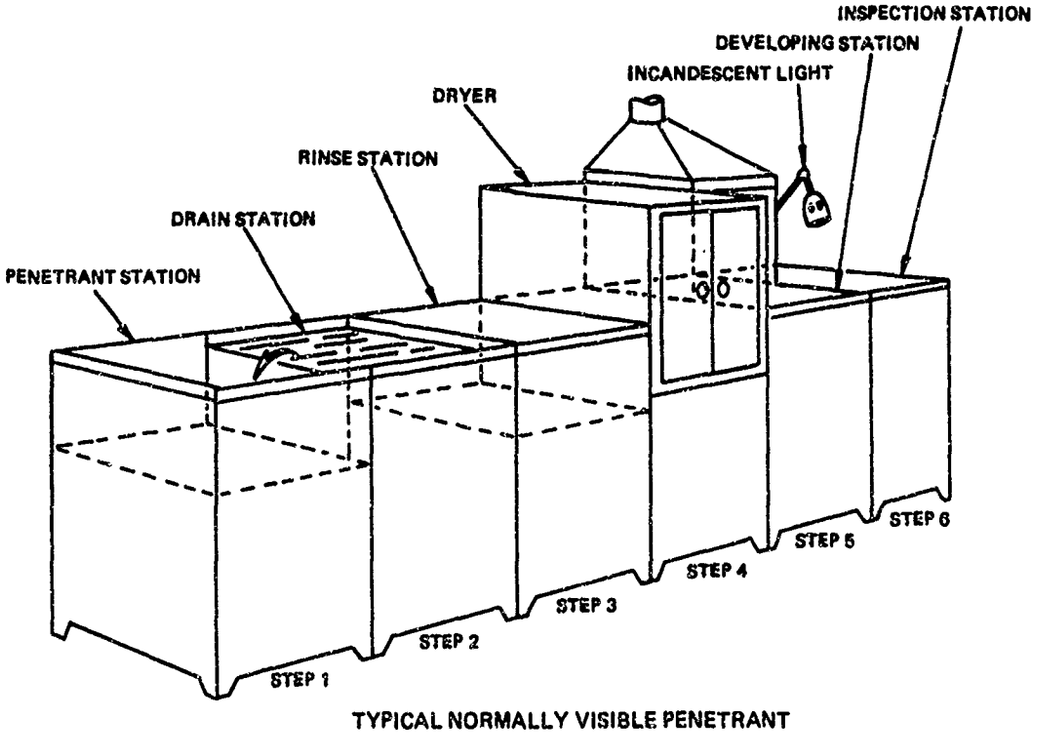
(7) Chemical etching. Test items that have been ground or machined may require etching using an acid or alkaline solution to open up grinding flaws and remove extraneous metal from surface flaws. If acid is used for etching, an alkaline solution is used as a neutralizing agent. If alkaline solution is used for the etching, then acid is used as the neutralizing agent. Either immersion tanks or applicators and wipe-off materials may be used in this type of cleaning.

8. EQUIPMENT

a. Stationary Penetrant Test Equipment. Arrangement of liquid penetrant test equipment depends on the type of process used and can readily be changed to meet requirements. (See Figure 3.)



TYPICAL FLUORESCENT PENETRANT TEST EQUIPMENT



TYPICAL NORMALLY VISIBLE PENETRANT

Figure 3. Typical Penetrant Test Equipment

Typically, the following arrangements are required for a post emulsification process:

(1) Pre-cleaning area (usually separate)
(2) Penetrant tank
(3) Drain station (next to penetrant tank)
(4) Emulsification tank
(5) Rinse tank
(6) Developer tank
(7) Drying oven
(8) Inspection booth with lighting facilities
(9) Post-cleaning area (usually separate).

Various equipment used in penetrant testing may include the following: pumps; hoses and applicators; lights (white and fluorescent); timers (to indicate soak and development time, and so forth); thermostats and thermometers; exhaust fans; spray guns; hydrometers (used to measure specific gravity of wet developers), and low-power magnifiers.

b. Portable Penetrant Test Equipment. When testing is required at a location remote from stationary equipment or when only a small portion of a large test item needs inspection, portable liquid penetrant kits may be used. Both fluorescent and white light type penetrants are available in kit form and include pressurized aerosol cans of penetrant. (The kits for fluorescent penetrant inspection include a black light.)

Most of the materials for penetrant inspection are available in spray cans or bulk quantities. Materials obtained from various suppliers usually differ enough so that it is necessary to use complementing materials from the same supplier in a given test. It is also necessary to comply with the suppliers instructions in the preparation and use of such materials.

c. Black Light Equipment. In fluorescent penetrant testing, black light equipment supplies light of the correct wavelength to make the penetrant fluoresce. Required equipment usually includes a current regulating transformer, a mercury arc bulb, and a filter. The transformer is usually housed separately and the bulb and filter are contained in a reflector lamp unit.

Fluorescent materials used in nondestructive testing generally respond most actively to radiant energy of a wavelength of approximately 3650 angstroms. This wavelength represents light just outside the visible range on the blue or violet side but not sufficiently far removed to be in the chemically active or ultraviolet range. Because of its lack of effect on the eye, it is generally referred to as "black light."

There are four possible sources of black light:

(1) Incandescent lamps.
(2) Metallic or carbon arcs.

(3) Tubular "BL" fluorescent lamps.
(4) Enclosed mercury-vapor arc lamps.

Because of insufficient output, instability, or other reasons, neither of the first two is practical for inspection use. Since the tubular fluorescent lamps are quite low in output, they are only usable in a very few special applications. This leaves only the mercury-vapor lamps which are almost universally used. Mercury-vapor lamps are gaseous-discharge devices. Within such lamps, an electric arc takes place in a controlled atmosphere and emits light having characteristics dependent on the nature of that atmosphere. A deep red-purple filter is generally used with black lights in penetrant testing and is designed to pass only those wavelengths of light that will activate the fluorescent material. Since dust, dirt, and oil greatly reduce the intensity of the emitted light, the filter should be cleaned frequently. Operators using the black light should be aware of the fact that the full intensity is not attained until the mercury arc is sufficiently heated. At least 5 minutes warmup time is required to reach the required arc temperature. Also, the light should be left on during the entire test period rather than being switched on and off since such switching shortens the life of the light.

9. INTERPRETATION OF TEST RESULTS

a. General. Penetrant testing is an effective method of nondestructive testing for surface flaws when properly conducted. The indications must be interpreted by qualified test personnel. It is important for test personnel to insure that a thorough inspection is made and that results are documented (written down in an official and organized manner that will allow repetition and verification of the test).

b. Indications. True indications are defined as those caused by a flaw in the material being inspected. False indications are penetrant deposits usually resulting from poor test practices.

The interpretation of an indication as being a true indication is based on careful observation and a thorough familiarity with penetrant process controls. A common source of false indications is insufficient washing of water-washable and post-emulsifiable penetrants. When fluorescent-type penetrants are used, a black light should be available during the washing process to allow the operator to insure that a good rinse is obtained and that fluorescent patches do not remain on the test item. When solvents are used in the removal process (rather than water), such patches are less likely to remain. Common types of penetrant indications include the following:

(1) Continuous lines. These may be caused by seam-type flaws.

(2) Intermittent lines. These may be caused by the same type of flaws that cause continuous lines except that portions of the flaw may have been closed by metal working processes.

(3) Round indications. These are usually caused by porosity-type flaws; e.g., pin holes, gas holes, or general porosity in the test item. Deep cracks may also appear as round indications when they trap a large amount of penetrant that spreads when the developer is applied. If a round indication appears in an isolated position (relative to other flaw indications), this often indicates a flaw of substantial depth and one that is not necessarily round.

(4) Small dots. These indications usually result from pin-hole type flaws, porosity, or cast alloy microshrinkage.

(5) Diffused or weak indications. These are often difficult to interpret. Such weak and diffused indications may be caused by surface porosity but more often are caused by: insufficient cleaning, incomplete penetrant removal, or use of excessive developer. When they appear, the test item should be thoroughly recleaned and retested. Typical penetrant indications are shown in Figure 4. In general, large flaws are brighter since they hold more penetrant. Shallow flaws generally appear as fine-line indications with a relatively low level of brightness.

c. Quality Control Procedures. Many quality control procedures for liquid penetrant tests are readily available from manufacturers and various societies such as ASTM. Tests required for oxygen compatible materials are described in applicable NASA specifications. When required, such tests must be accomplished in accordance with the procedures described in the detailed specifications. Preparation of reference standards for liquid penetrant test interpretation is thoroughly described in the literature.

General quality control procedures applicable to liquid penetrant testing also include tests of the penetrant (sensitivity, water content, viscosity, fluorescent penetrant fade) and of the emulsifier (water washability).

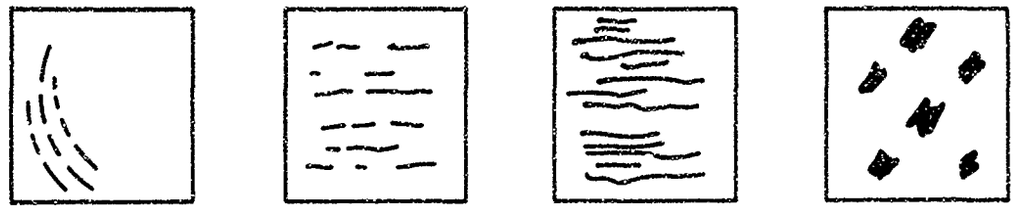
10. SAFETY PRECAUTIONS

If normal precautions are taken, little danger exists in the application of penetrant test materials. To prevent unnecessary contact with penetrant materials, however, test personnel should wear waterproof aprons and gloves.

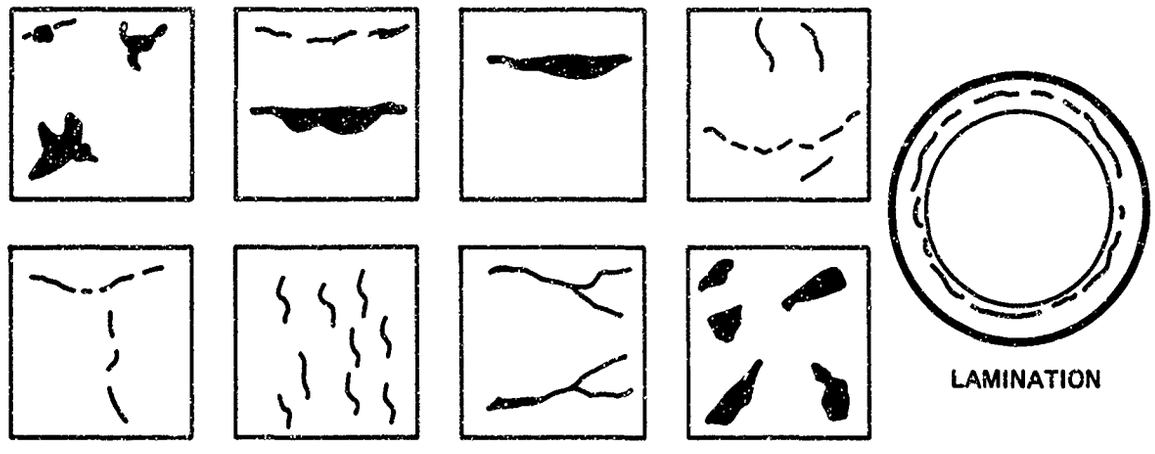
Hand creams may be used to avoid the drying action caused by certain penetrant materials. Soap and water should be used to remove penetrant materials that have come in contact with the skin.

11. ELECTRIFIED PARTICLE NDT

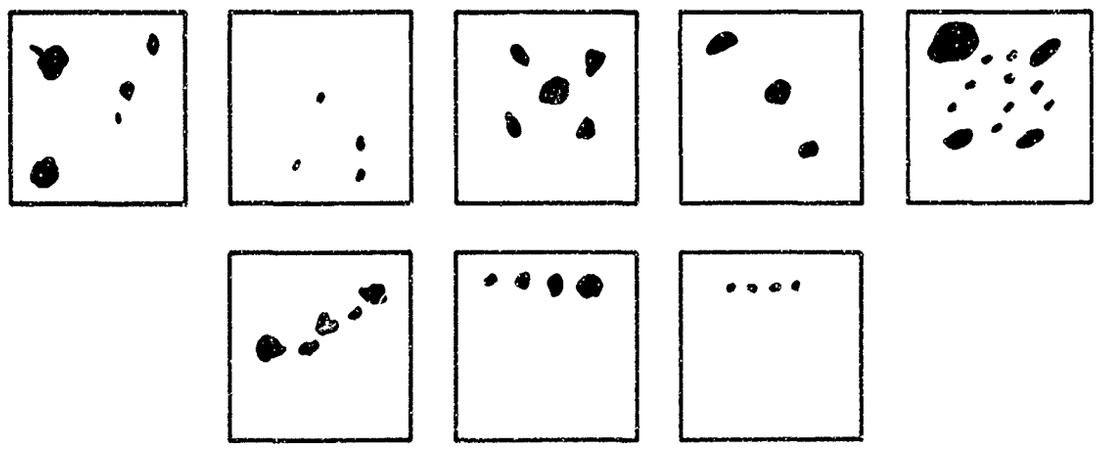
Although electrified particle testing is not a liquid penetrant test, it is an important test especially in the area of ceramics. A brief discussion of this method is included here since — like liquid penetrant testing — it is useful for test of nonconducting materials.



TYPICAL NON-RELEVANT INDICATIONS



TYPICAL TRUE INDICATIONS



TYPICAL ROUNDED INDICATIONS

Figure 4. Typical Penetrant Indications

The electrified particle method of NDT provides a means of detecting small flaws in a truly nonconducting material such as glass, ceramics, and porcelain enamel. It can be used to detect cracks finer than those observable by microscope, penetrants, or electron microscope. Cracks well below 0.1 micron (4 ten-millionths of an inch) can be located and clearly marked with a distinct powder indication, even at production-line speeds.

Separate techniques are used for nonconducting materials with and without metal backing. To inspect a product or material that contains no metal, the test part is dipped or sprayed with water-base conductive penetrant which enters the cracks. The surface is dried with a cloth, air blast, hot air drier, or other means, and a cloud of fine electrostatically charged particles is blown on the nonconducting surface to be tested. The charged particles quickly build up to a highly visible powder indication.

To test a nonconducting material such as porcelain enamel backed by metal, the charged powder is blown directly at the surface to be inspected. If a crack is present, electrons in the base metal leak through and attract the positively charged particles. A ridge of powder builds up, thus indicating the presence of the crack. A crack must be open to the surface to be detected.

12. ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Tests are quick, easily applied, and relatively inexpensive.

(2) Liquid penetrants are very sensitive to fine surface cracks.

(3) Liquid penetrants can be applied to the surface of complexly shaped objects.

(4) Enlarged images of small flaws can be obtained with optical aids.

b. Disadvantages.

(1) The surface must be clean and dry before the penetrant is applied; otherwise, surface contamination may interfere with the tests.

(2) The penetrant should be used on objects that are near room temperature since low temperatures can cause the penetrant to become highly viscous or to solidify, and high temperature can cause the penetrant to evaporate or flash.

(3) Initial penetrant tests may interfere with subsequent tests.

(4) Liquid penetrant tests give no indication of flaws not open to the surface.

(5) Shallow or broad flaws are difficult to detect since the penetrant is easily removed from them when the excess penetrant is being removed. (Inspection of such flaws can be aided to a certain extent by carefully selecting a penetrant of a suitable viscosity.)

(6) It is often difficult to remove all of the penetrant from the object at the conclusion of an inspection. (This may or may not be a serious disadvantage.) Correct post-cleaning eliminates trouble. Selection guides and MIL Specs are available to provide guidance in cleaning test items.

Section IV. MAGNETIC PARTICLE INSPECTION

13. BACKGROUND

Magnetic particle testing is a nondestructive test method for detecting flaws at or near the surface in ferromagnetic materials. The method consists essentially of magnetization of the article, application of magnetic particles, and interpretation of the magnetic particle patterns.

Magnetic particle testing is a relatively simple method. It is almost completely free from any restriction as to size, shape, and heat treatment of a ferromagnetic test item because either the whole part or selected portions can be magnetized. The medium used is finely divided particles of ferromagnetic material which can be applied in dry powder form or suspended in a liquid. These particles are applied to the surface of the test item which has been suitably magnetized. The particles are attracted to areas of nonuniformity associated with flaws. A crack or other flaw in a magnetized test item disrupts the even flow of the lines of force.

For best sensitivity, the magnetizing current must flow in a direction parallel to the principal direction of the expected flaw. Circular fields may be produced by passing a current through the test item and are almost completely contained within the test item. Circular fields can also be produced by placing a central conductor in the test item or by prods. (See Figure 5.) Longitudinal fields are produced by using coils or yokes. (See Figure 6.)

Application of particles while the magnetizing current is on is known as the continuous technique. This technique produces indications stronger than those obtained by the residual technique which relies on the residual magnetism remaining in the test item after the current is turned off.

14. SURFACE CLEANING

a. Cleaning Before Testing. The test item should be thoroughly cleaned prior to testing. Cleaning may involve removal of flake, slag, heavy build-up of paint, rust, grease, or other materials, which could interfere with the final test result. Sandblasting equipment, wire brushes, files, chipping

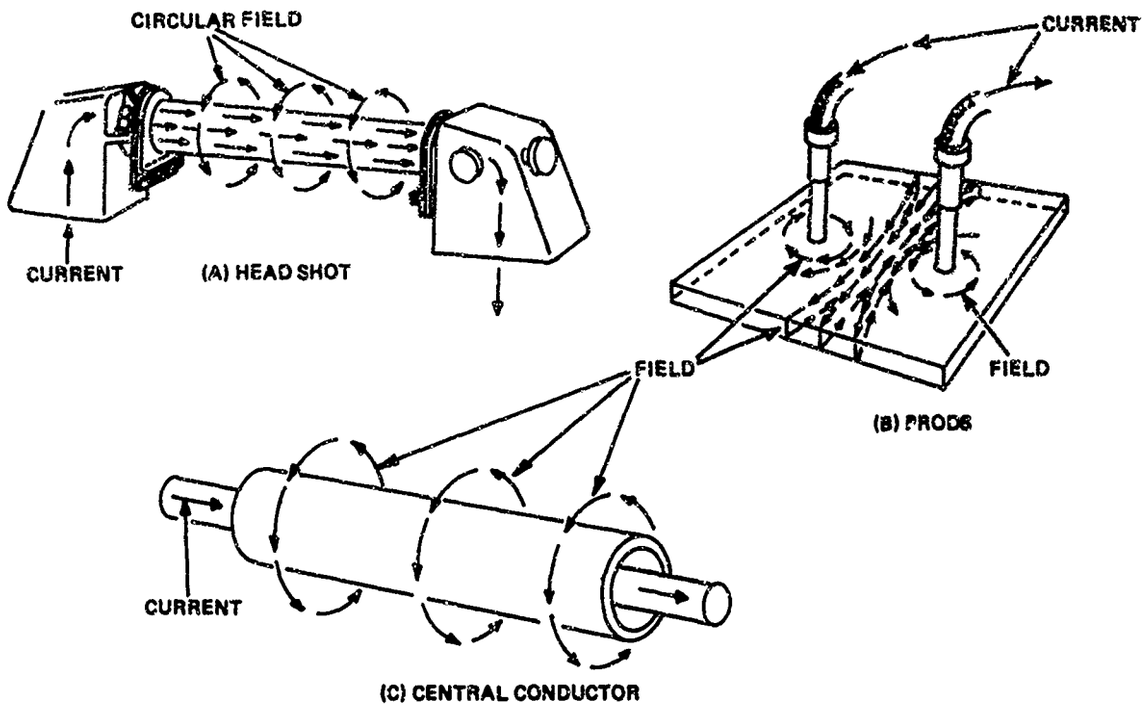


Figure 5. Circular Magnetization by Direct and Indirect Current Induction

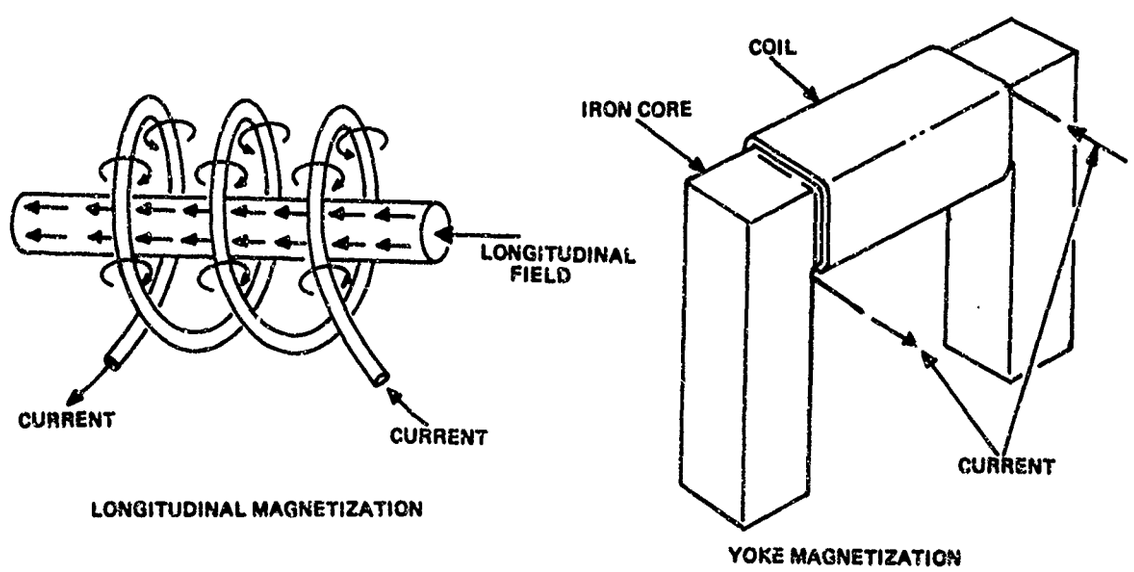


Figure 6. Longitudinal Magnetic Fields

hammers, and so forth, may also be used depending on the item, size, and other factors. The cleaning technique used should depend upon the requirements and conditions of the particular test item involved. Approved chemical cleaning methods may also be used. Smooth surfaces and uniform color are desired for optimum formation and examination of the magnetic particle pattern. When it is necessary to perform magnetic particle testing on items that have been covered with anti-corrosive protective coatings (such as primers, paints, or cadium-, chromium-, nickel-, or zinc-plating), the coatings do not necessarily have to be removed, since flaw indications are not usually affected. The acceptable thickness limits for such coatings on test items should be checked before conducting a test. In certain cases, coatings are purposely applied to the test item to provide a contrasting background for the medium. Before an item is tested, it is sometimes necessary to plug holes or openings in the test item that may affect magnetization.

b. Cleaning After Testing. Magnetic particles should be completely removed from all test items after test and demagnetization. Cleaning may be accomplished by use of compressed air, solvents, washes and wiping equipment suitable to the size and complexity of the task. After being cleaned, the test item should be returned to its original state by removing all of the plugs used to seal holes and cavities during the test process.

15. SELECTION OF MEDIUM (MAGNETIC PARTICLES)

a. General. Considerable importance is attached to the knowledge of available detecting mediums. Four properties enter into the selection of a satisfactory medium: magnetic, geometric, mobility, and visibility.

(1) Magnetic Properties. It is desirable that the particles of the testing medium possess two important properties: high permeability and low retentivity. Permeability may be defined as the degree of ease with which a particle is magnetized. Retentivity is that property which enables particles to hold (to a greater or lesser degree) a certain amount of residual magnetism. Particles incorporating high permeability and low retentivity give maximum response in a leakage field, and at the same time do not remain magnetized when they pass out of the influence of the magnetic field.

(2) Geometric Properties. The spherical shaped particle offers a high degree of mobility but has low attractive power. The long slender jagged particle has a high degree of attractive power and low mobility. A multi-facet nugget type particle is a good compromise in that it reasonably combines the optimum qualities of the other two types.

Particle size is also an important consideration, and it is desirable to have particles of various sizes. This is because small particles are required to bridge a tight-lipped crack. Larger sizes are necessary for wider cracks. A weak leakage field is unable to hold a large particle but is able to fix and retain one of smaller size. Thus, dry powder magnetic particles are usually available in a wide range of sizes — but all are small enough to pass through a 100-mesh screen.

In the wet technique of magnetic particle testing, magnetic oxides of iron are generally used. Although they are extremely fine in size, they are of lower permeability than the metallic dry particles and have neither the most desirable shape nor variety of sizes available in metallic particles. Fine magnetic oxides are generally used in the wet technique because they can be suspended in a liquid when a dispersing agent is employed.

(3) Mobility. When the particles are brought into the influence of the leakage field of a flaw, they are free to form a pattern or indication. This freedom is influenced by condition, shape, and application of the particles.

In the dry particle technique of magnetic particle testing, particle mobility is obtained by dusting or blowing the particles over the surface of the article. This permits the flaw to catch and hold some particles as they move by. Mobility is also obtained by vibrating the article after the particles have been applied. Alternating current may be used advantageously because the alternating field causes the particles to "dance" and thus enhances mobility. However, direct current is generally considered superior in overall test characteristics.

The principal advantage of the wet technique of magnetic particle testing is the excellent mobility (freedom to move in the three dimensions) of the suspended particles. It is important to use a low viscosity liquid so that the suspended particles are retarded as little as possible by the liquid in which they are suspended.

(4) Visibility. So that an indication can be made readily visible, a good light source is essential. Particle color also affects visibility. With various types of surfaces (from highly polished articles to rough castings), no one color of particle is always satisfactory. The choice of particle color is entirely dependent on the test item. The most widely used particles are gray, red, and black. The gray powder has excellent contrast against practically all surfaces (with exception of certain silver-gray sand-blasted surfaces). Particles coated with a fluorescent dye often are used to enhance visibility.

16. TECHNIQUES

a. General. Dry magnetic particles are commonly applied from shaker cans, pressure bulbs, or spray guns. The first two are the simplest but not necessarily the best. Automatic particle blowing equipment is usually more economical and satisfactory for larger inspection tasks.

When the wet technique is used, wet suspensions can be caused to flow over the surface to be examined, or the test item can be immersed in a bath in which the particles are suspended. The immersion bath technique is normally used with the residual magnetism technique and wet suspensions flowing over the article are usually used with the continuous magnetism technique.

b. Particle Requirements. The particles composing the medium in both the wet and dry method should have the following characteristics:

(1) Ferromagnetic
(2) High permeability
(3) Low retentivity
(4) Finely divided
(5) Free of contaminants
(6) Nontoxic
(7) High color contrast (visibility)
(8) Correct size range.

17. ELECTRIC CURRENT REQUIREMENTS

The current used in magnetic particle testing may be alternating, full wave direct (fwdc), or half-wave direct (hwdc). The hwdc is most effective for locating subsurface flaws. (Refer to Figure 7.) The required amount of magnetizing current is affected by the permeability of the metal, the shape and thickness of the test item, and the type of flaw sought. The length of a test item does not affect the current requirement, because the current flow in a uniform cross section is uniform throughout the length of the item. The electrical reluctance of the item, however, increases with length, therefore requiring more energy to develop the same amperage (or field) through a long test item. When a test item is not uniform in section, it is necessary to use a lower value of current for the thinner sections and higher second, third, or more values of currents for heavier sections. Equipment is available that will magnetize a test item in two directions.

It is always considered appropriate to use a lower current value first to test a thinner section and then successively higher currents for the testing of increasingly larger sections of a test item. A residual field from a preceding magnetization will be automatically demagnetized by a magnetizing

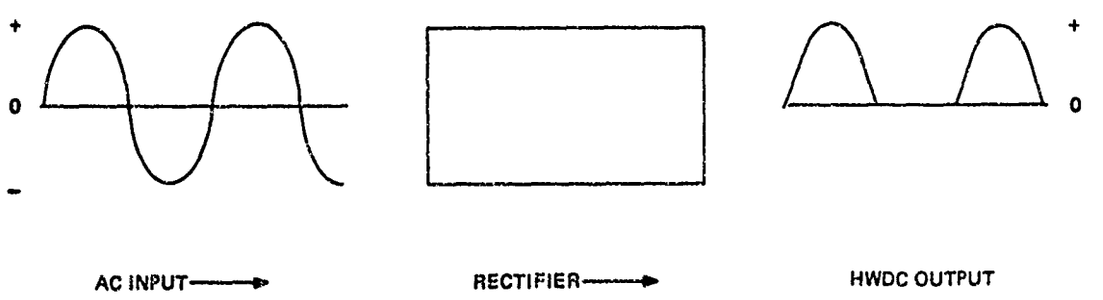


Figure 7. Half-Wave Direct Current Used in Magnetic Particle Testing

force equal to or of higher magnitude than the previous one. If a magnetization using a higher current value is used first, it is necessary to demagnetize the test item before applying a lower current. The reverse or opposing magnetizing force required to reduce the residual magnetic induction to zero is termed coercive force. A field indicator is used after performing demagnetization on a test item to insure that the residual field strength has been reduced to the desired level.

18. INTERPRETATION OF FLAWS

a. General. In a comprehensive view of the entire list of flaws which can be located by magnetic particle testing, it is logical to think of the life history of the metal, from the time it first solidifies from the fluid state, down through its fabrication into useful form, and finally, ending when it has worn out or has fractured (as a result of fatigue or other causes).

Magnetic particle indications from flaws located on the surface usually appear as sharp distinct lines. Subsurface flaws appear as irregular, rough, and hazy indications. The width of a subsurface flaw indication generally varies with its size and depth. Correct interpretation of indications caused by subsurface flaws requires a considerable amount of skill on the part of the inspector.

(1) Surface Indications. As a class, surface flaws tend to produce sharp, distinct, clean-cut, and tightly held indication patterns.

(2) Subsurface Indications. Subsurface flaws tend to produce indications which are less distinct, forming diffused or fuzzy patterns rather than the sharp-outlined indications observed from surface flaws.

(3) Nonrelevant Indications. The group of magnetic disturbances that are not caused by flaws or actual breaks in the metal, must be recognized as nonrelevant. Otherwise, entirely wrong interpretations may lead to scrapping of acceptable test items. The causes of nonrelevant indications are numerous. They may result from distortions of fields caused by abrupt variation in the test item shape. Rough surfaces can cause a mechanical rather than a magnetic hold on the testing medium and cause such nonrelevant indications. Close examination usually reveals that such indications are nonrelevant.

19. PRESERVATION OF INDICATIONS

It is often desirable to preserve magnetic particle indications for future reference. There are a number of methods by which this can be accomplished. A transparent lacquer may be sprayed over the flaw. Spraying or dipping are more effective than brushing because the latter, no matter how carefully done, tends to disturb and mar the pattern. Stock lacquers are generally thinned at least three to one before being used for this purpose. The magnetic field can be applied before the lacquer sets, and the pattern

becomes permanently fixed after the lacquer dries. A white lacquer with black paste in suspension gives a readily visible black pattern on a white background and can be applied on practically any surface. If desired, the lacquer can be applied first, allowed to dry, and the powder applied afterwards. The resultant patterns can then be photographed. Where adaptable, a camera containing a self-developing film may be used so that test results are immediately available.

A convenient and widely used method of preserving indications and patterns is the transparent tape technique. If the dry magnetic particle method is used, the excess powder is blown carefully away or otherwise removed. If the wet method is employed, sufficient time is allowed for the solvent to evaporate from the particles composing the indication. A strip of transparent tape may then be carefully placed over the indications and gently pressed down with the fingers or a rounded stick. The tape may then be peeled off, bringing the indication with it. If desired, the strip may then be placed on white paper and photographed, traced on tracing paper for blueprinting, or merely kept in a permanent record book. With care, the transferred pattern will remain well-defined and accurate in every detail and may serve as well as the original pattern for studying the indication.

20. MAGNETIC PARTICLE EQUIPMENT

a. General. The following should be considered when selecting equipment for magnetic particle testing:

(1) Requirements for wet or dry method.

(2) Magnetization requirements (based on test item configuration, etc.).

(3) Degree of automation.

(4) Demagnetization (whether incorporated or separate equipment).

(5) Amperage required.

(6) For wet technique, tank capacity in gallons.

(7) Air supply requirements.

(8) Line voltage requirements.

(9) Accessories required.

b. Stationary Equipment for Use with the Wet Technique. Magnetic particle equipment for wet-type testing can be built so that test items of practically any length can be tested. Typical equipment, such as that illustrated in Figure 8, enables magnetization of test items ranging from a few inches to approximately ten feet in length. To test an item, circular or longitudinal magnetization is possible.

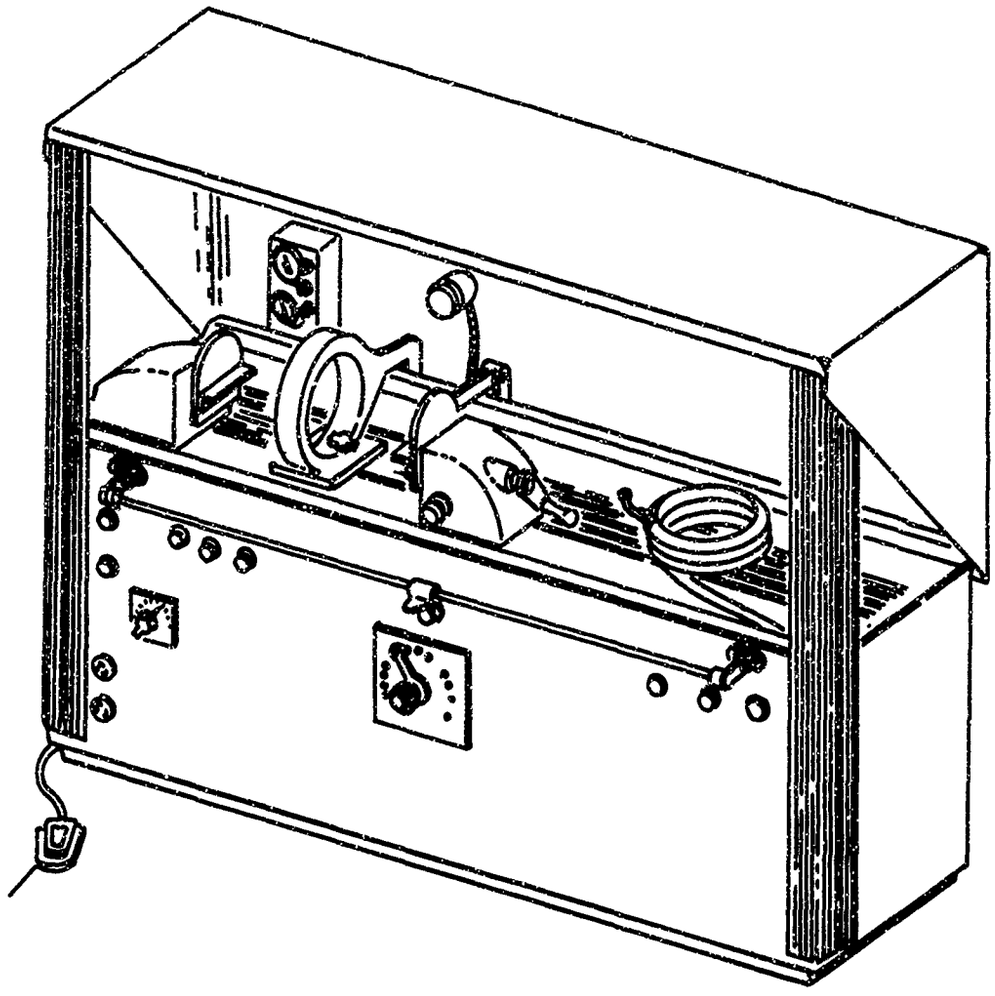


Figure 8. Stationary Magnetic Particle Test Equipment

c. Mobile Equipment. A typical mobile piece of magnetic particle equipment is illustrated in Figure 9. This type of equipment operates on 220/440 volt ac input and provides both a variable ac and half-wave dc of approximately 3000 amperes output. Selection of ac or half-wave dc is easily changed by switching cables on cable lugs located in front of unit. Cables ranging from 15 to 30 feet may be further extended by additional lengths, to as much as 90 to 100 feet. When extension cables are used, a decrease in current output can be expected although prods are usually used with mobile equipment, solenoid or cable wrapping techniques can be used. Also, use of a central conductor hooked up between the two cables facilitates variation in test techniques. Dry magnetic particle powder is most often used with this type of equipment but the wet technique (with an external tank) or materials in kit form can also be used.

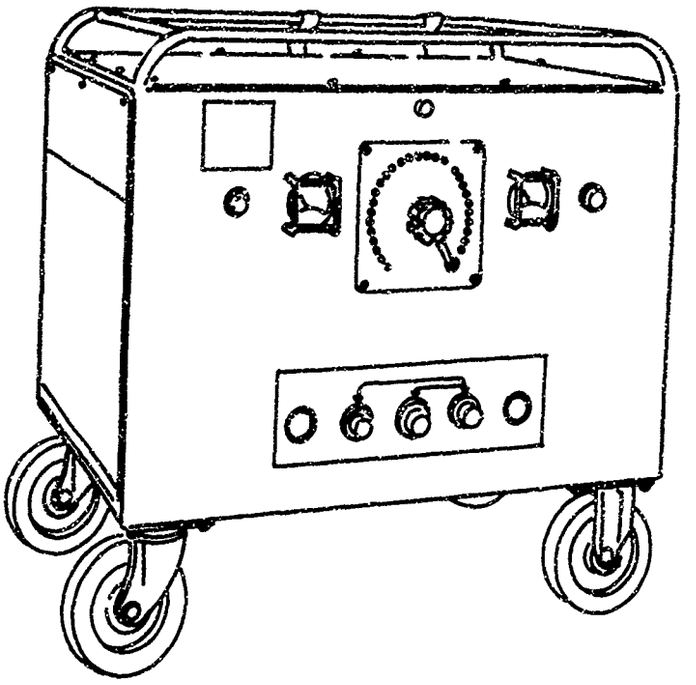


Figure 9. Mobile Magnetic Particle Test Equipment

d. Demagnetization Equipment. Most common types of demagnetization equipment consist of an open tunnel-like coil through which ac at the incoming frequency (usually 60 cycles) is passed. (See Figure 10.) The larger type of equipment is frequently placed on its own stand and incorporates a track or carriage to facilitate moving large and heavy articles. Smaller demagnetization equipment such as table-top units, yokes, or plug-in cable coils, may be feasible for demagnetization of small test items. The large stationary type equipment is preferable when multidimensional test items are involved.

e. Accessories. The number of accessories used in magnetic particle testing are extensive. Some are available from the manufacturers of magnetic particle equipment; others are made up for specific purposes. Accessories usually depend on the type and method or application of the test selected. Such accessories are chosen primarily to facilitate and enhance the quality and performance of a given test or test technique. The following list contains frequently used accessories and their applications.

(1) Cables -- used with mobile equipment to carry the current to prod or solenoid.

(2) Prods -- used for magnetizing of welds, sheet, or plate.

(3) Clamps -- used instead of prods to facilitate good contact with article or when one-man operation is required.

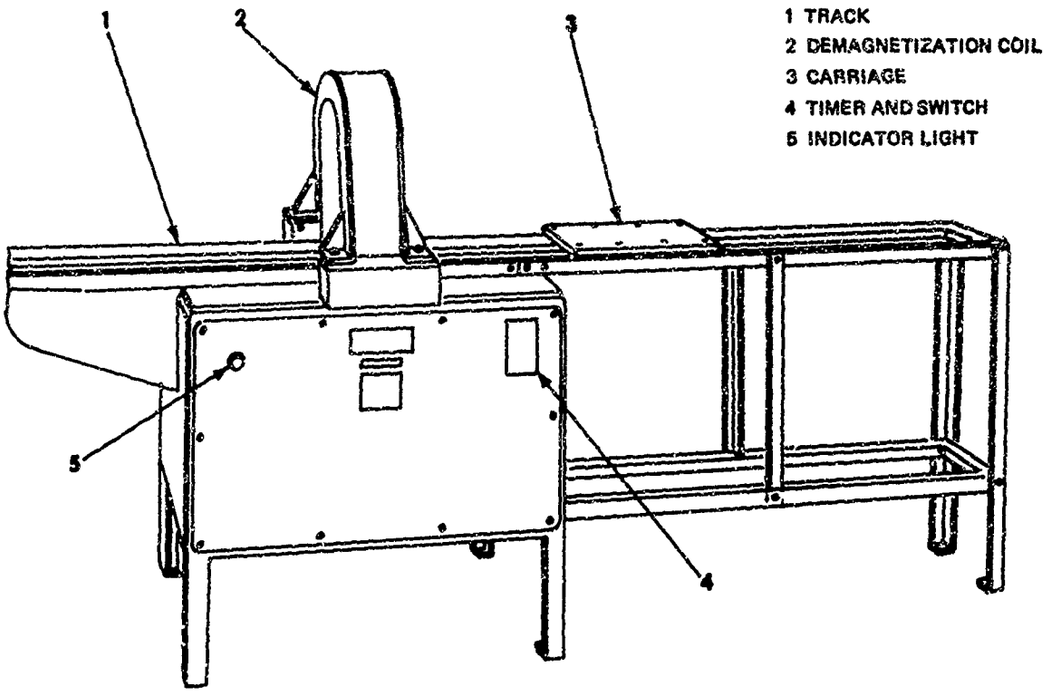


Figure 10. Demagnetization Equipment

(4) Contact Blocks -- used to facilitate cable connection from stationary equipment for external use of prods or coils.

(5) Demagnetizing Unit -- used to demagnetize ferrous metals containing residual magnetism.

(6) Field Indicator -- used in measuring residual magnetism in an article.

(7) Leeches -- used as prods or clamps.

(8) Liquid Applicator -- used in applying fluorescent or nonfluorescent test medium: can be manual, electric, or air operated.

(9) Mesh -- used between contact points and article tested to avoid sparking and burns.

(10) Powder Applicator -- used to apply magnetic particle powder to the test area: can be a powder-puff or powder blower.

f. Black Light. The use of black light is standard in fluorescent type inspection. In some instances, more than one black light may be desirable. A portable type black light may be used with mobile equipment when wet method testing is performed.

21. SAFETY PRECAUTIONS

Magnetic particle inspection involves very few safety hazards. However, the normal precautions when working with electrical equipment should be taken. Also, the normal precautions when working with black lights should be observed, as was mentioned under safety aspects of penetrant testing, i.e., cracked or broken lights should be replaced immediately to avoid possible harmful exposure to ultraviolet rays. When testing an item, a sample item should be tested first so that current adjustments and so forth can be made to avoid test item damage such as prod burns.

22. ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Tests are relatively simple.

(2) Tests are highly sensitive to small crack-like flaws in ferromagnetic materials.

(3) Heat treatment of test material will not interfere with inspection.

b. Disadvantages.

(1) Only ferromagnetic materials can be tested.

(2) Only surface or near-surface flaws can be detected.

(3) The depth of a flaw cannot be determined directly.

(4) Several directions of magnetization are often required for complex shapes.

(5) Surface contamination (such as rust or slag) may interfere with the tests.

Section V. X- AND GAMMA-RAY FILM RADIOGRAPHY

23. BACKGROUND

a. General. The German physicist, Roentgen, discovered X-rays in 1895 while working with a high voltage gaseous discharge tube. Electrons were emitted from a cathode and accelerated toward a target which they

struck with high velocity. He found that a highly penetrating radiation was emitted from this bombarded target. Very soon thereafter, it was learned that this radiation could be used to penetrate the human body and solid materials. Radiology and radiography were soon established for use in medical work and nondestructive testing.

X-rays are a form of electromagnetic radiation produced by means of a high voltage gaseous discharge tube. They are usually produced by causing a stream of high energy electrons to impinge on a metallic target in an X-ray tube, thus producing photons by deceleration of the electrons.

Gamma rays are electromagnetic radiation of nuclear origin produced from man-made or natural isotopes. Gamma rays are emitted by atomic nuclei in a state of excitation, and have very short wavelengths.

An early method of detection used to study the mysteries of radiant energy beyond the ultraviolet region was the use of inorganic chemicals which fluoresce when irradiated. These fluorescent materials absorb short wavelength invisible X-radiation and reradiate the energy at a longer visible wavelength. A more detailed discussion of fluoroscopy and X-ray imaging devices is provided in the next section. This section will provide a very general coverage of X- and gamma-ray radiography.

Radiography is one of the oldest NDT methods and has been used at least since the early 1920's. X- and gamma-rays are often referred to as penetrating radiation.

X- and gamma-rays have the following characteristics:

(1) X-rays are in the range of 0.5 to 0.0004 angstroms (Å).

(2) Gamma rays are in the range of 0.1 to 0.005 angstroms (Å).

(3) Both are invisible electromagnetic radiation.

(4) Both can penetrate matter.

(5) Both are differentially absorbed.

(6) Both travel in straight lines.

(7) They travel with a velocity of approximately 186,000 miles/sec.

(8) They cause some substances to fluoresce.

(9) They are not usually affected by electric or magnetic fields.

(10) They ionize gases as they pass through them.

(11) They produce photochemical effects in photochemical emulsions.

(12) They are capable of liberating photoelectrons.

b. Use of X- and Gamma-Rays in NDT. Use of X- and gamma-rays in NDT is based on the principle of differential absorption. A common technique used for recording the results of using X- and gamma-rays to irradiate material, is by means of photographic emulsion or X-ray film.

Three characteristics of the radiation permit its use in producing radiographs:

(1) The radiation penetrates the test item.

(2) The penetrating radiation travels in straight lines and is differentially absorbed.

(3) The radiation exposes the film (ionizes the tiny silver bromide grains in the film emulsion) forming a latent image.

The ability of a given test item to block or partially block the passage of penetrating radiation through the material is termed absorption. In general, as the absorption abilities of a test item increase, penetration decreases. For a given intensity, such absorption depends on the density of the material as well as its thickness. For example, lead absorbs more radiation than iron because lead is more dense. Figure 11 illustrates the principles of penetration and differential absorption.

The test item absorbs less radiation where it is thin or a void exists. The latent image produced in the film as a result of the radiation passing through, becomes a shadow picture of the test item when the film is processed. Since more radiation passes through the test item in the thin and less dense areas, the corresponding areas of the film are darker.

The sharpness of the film image is influenced by the size of the radiation source and the ratio of the source-to-test-item distance and test-item-to-film distance. Figure 12 shows a small geometrical unsharpness (penumbra) when the test item (represented by "O") is close to the film "F". Optimum geometrical sharpness of the image is obtained when the radiation source is small, the distance from the source to the test item is relatively large, and the distance from the test item to the film is relatively small. (See Figure 13.) If the plane of the test item and the plane of the film are not parallel, image distortion results. The same is true if the radiation beam is not directly perpendicular to the film plane. Whenever film distortion is unavoidable (as a result of physical limitations of a test), it should be remembered that all parts of the image are distorted; otherwise, an incorrect interpretation could result. (See Figure 14.)

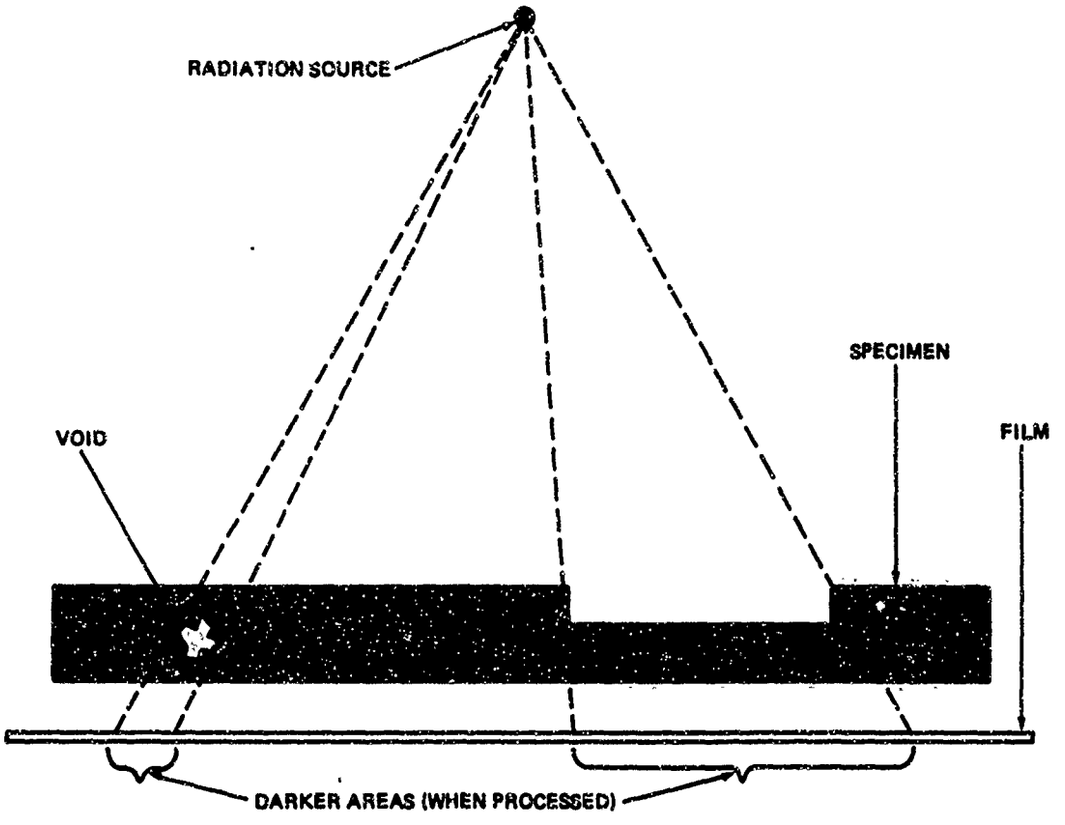


Figure 11. Basic Radiographic Process Showing Differential Absorption

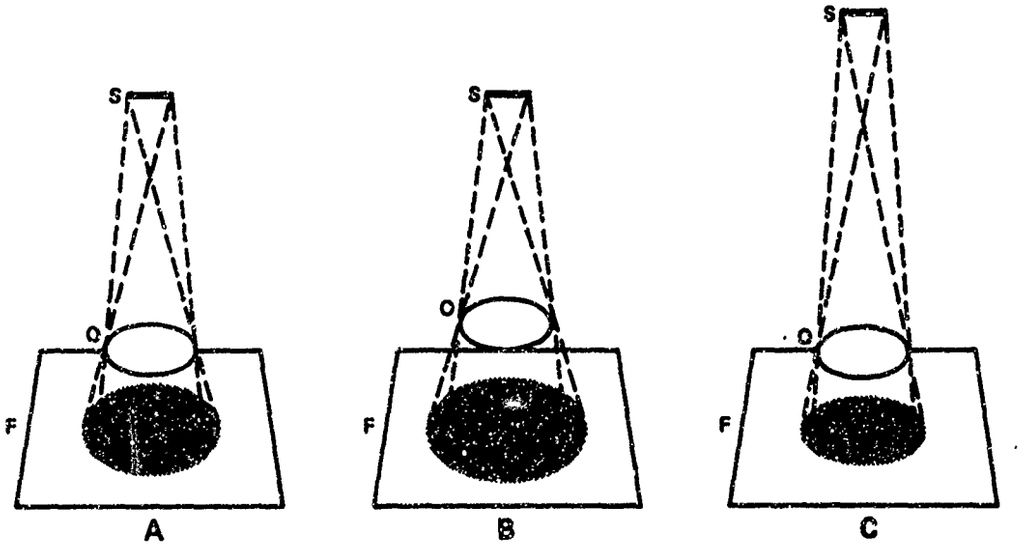


Figure 12. Image Sharpness, Penumbral Shadow

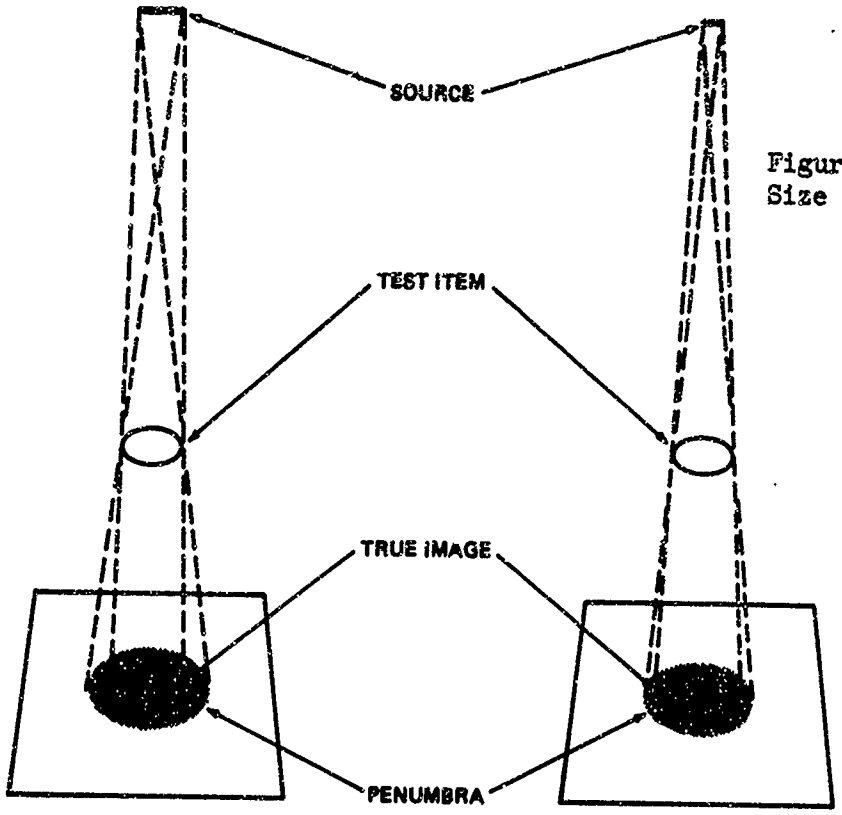


Figure 13. Effect of Source Size on Image Sharpness

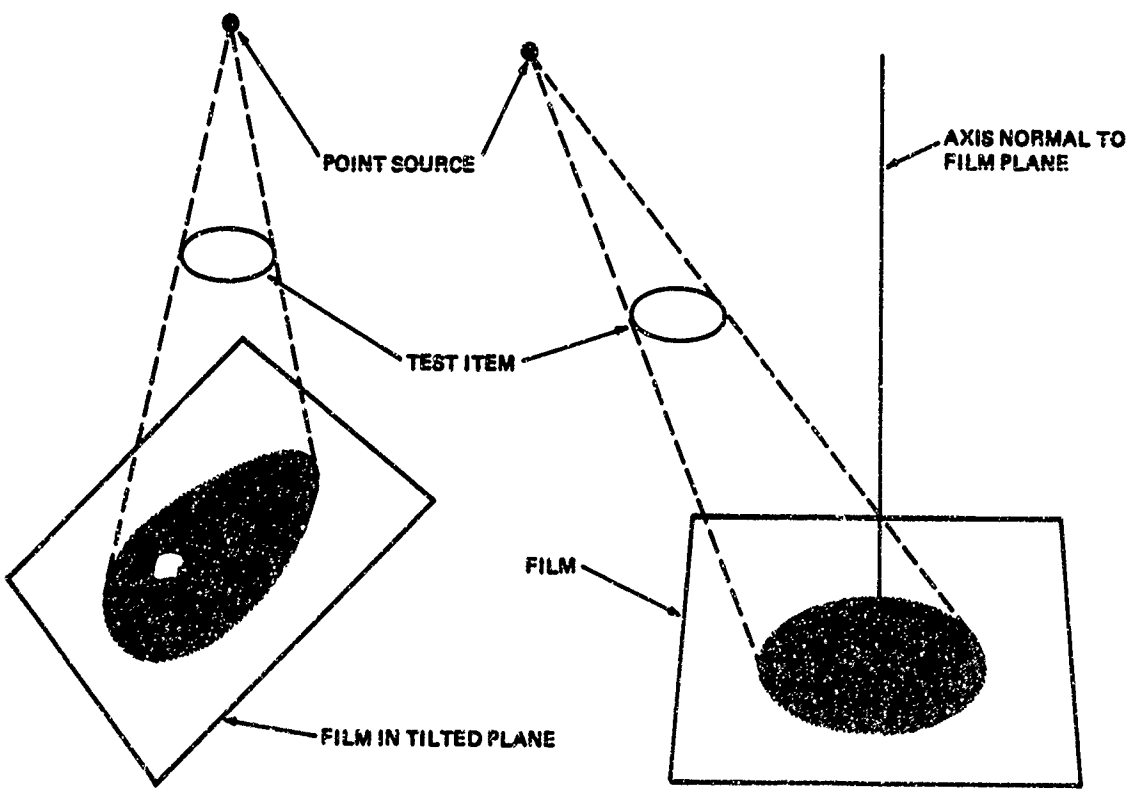


Figure 14. Angular Image Distortion

24. X-RAY GENERAL INFORMATION

a. Introduction. X-rays and electromagnetic waves of lower energy are generated when rapidly moving (high-energy) electrons are caused to interact with matter in a suitable environment such as that provided by the X-ray tube. When an electron of sufficient energy interacts with an orbital electron of an atom, a characteristic X-ray is generated. It is called "characteristic" because its energy is determined by the characteristic composition of the disturbed atom. When electrons of sufficient energy interact with the nuclei of atoms, bremsstrahlung (continuous X-rays) are generated. They are called continuous because their energy spectrum is continuous and is not entirely dependent upon the characteristics of the disturbed atoms. To create the conditions required for the generation of X-rays, there must be a source of electrons, a target for the electrons to strike, and a means of accelerating the electrons in the desired direction. X-rays of a variety of wavelengths result when high-speed electrons in a vacuum tube are suddenly stopped by a metal target. An X-ray tube contains a heated filament (cathode) and a target (anode). In practical applications of X-ray generation, a solid material of high atomic number, usually tungsten, is used for the target. In an X-ray tube, the target is a portion of the tube anode. (See Figure 15.)

(1) Inverse Square Law. The intensity of an X-ray beam varies inversely with the square of the distance from the radiation source. X-rays, like visible light rays, diverge upon emission from their source and cover increasingly large areas as the distance from the source increases. This relationship is known as the Inverse Square Law. It is a major consideration in computing radiographic exposures and safety procedures.

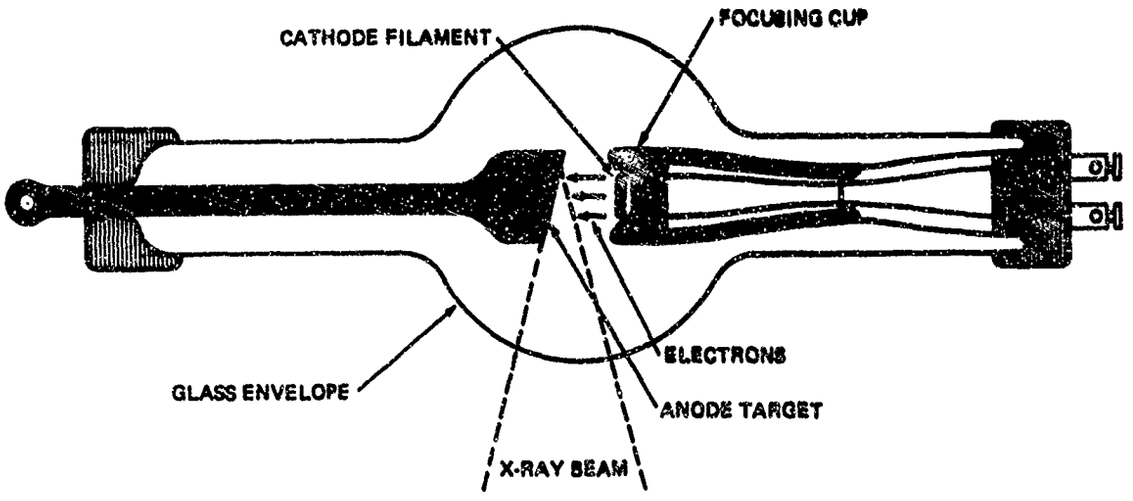


Figure 15. Basic X-Ray Tube

(2) Intensity. X-ray beam intensity is dependent upon the number of electrons available at the X-ray tube cathode. If all other factors remain constant, an increase in the current through the tube filament will increase the cathode temperature, cause emission of more electrons, and thereby increase the intensity of the X-ray beam. Similarly, though to a lesser degree, an increase in the positive voltage (usually expressed in kilovolts) applied to the tube anode will increase the beam intensity because more of the electrons available at the cathode will be attracted to, and collide with, the target. Because the intensity of the generated beam is almost directly proportional to the flow of electrons through the tube, the output rating of an X-ray machine is often expressed in milliamperes (ma) of current flow. This same direct proportion establishes tube current as one of the exposure constants of X-ray radiography.

The intensity of the radiation used in radiography is almost directly proportional to filament current. Tube voltage determines the penetration energy of the rays. As tube voltage increases, shorter wavelengths and more intense X-rays are produced. When the energy of penetrating radiation increases, the difference in attenuation between materials decreases. Consequently, more film image contrast is obtained at lower voltage. Film contrast is defined as the measure of difference in the film blackening as a result of various X-ray intensities transmitted by the object and recorded as density differences in the image. Thus, the degree of film blackening from one area to another is contrast. An increase in applied voltage increases the intensity (quantity of X-rays) but of more importance to the radiographer is that higher voltage generates higher energy rays having greater penetrating power. High energy (short wavelength) X-rays are known as hard X-rays, and low energy (longer wavelength) X-rays are known as soft X-rays.

b. Direct and Scattered Radiation. Exposure of a radiographic film results from direct and scattered radiation. The image-forming radiation is direct. Scattered radiation produces undesirable images on the film and loss of contrast and occurs in the item being X-rayed or in neighboring objects.

(1) Internal Scatter. Internal scatter is the scattering that occurs in the test item being radiographed. (See Figure 16.) It is reasonably uniform throughout a test item of one thickness, but affects definition by blurring the image outline. Scatter radiation obscures the edges of the test item and the hole through it. The increase in radiation passing through matter due to scatter in the forward direction is known as buildup.

(2) Side Scatter. Side scatter is the scattering from walls, or objects in the vicinity of the test item, or from portions of the test item, that causes rays to enter the sides of the test item. As shown, side scatter obscures the image outline just as internal scatter does. (See Figure 17.)

(3) Back Scatter. Back scatter is the scattering of rays from surfaces or objects beneath or behind the test item. Back scatter also obscures the test item image.

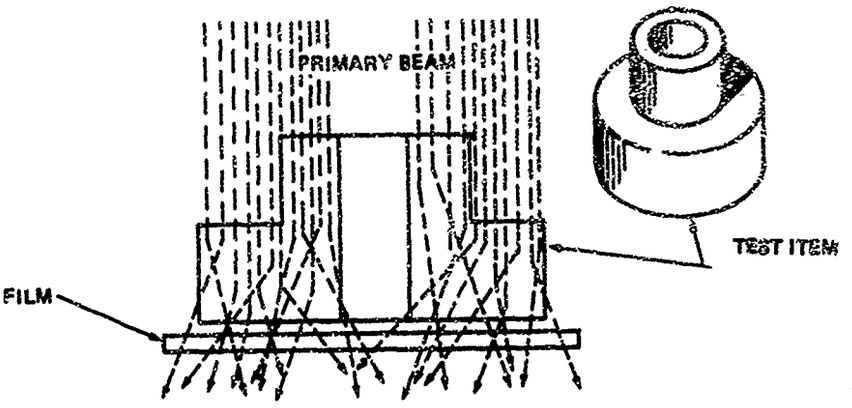


Figure 16. Internal Scatter

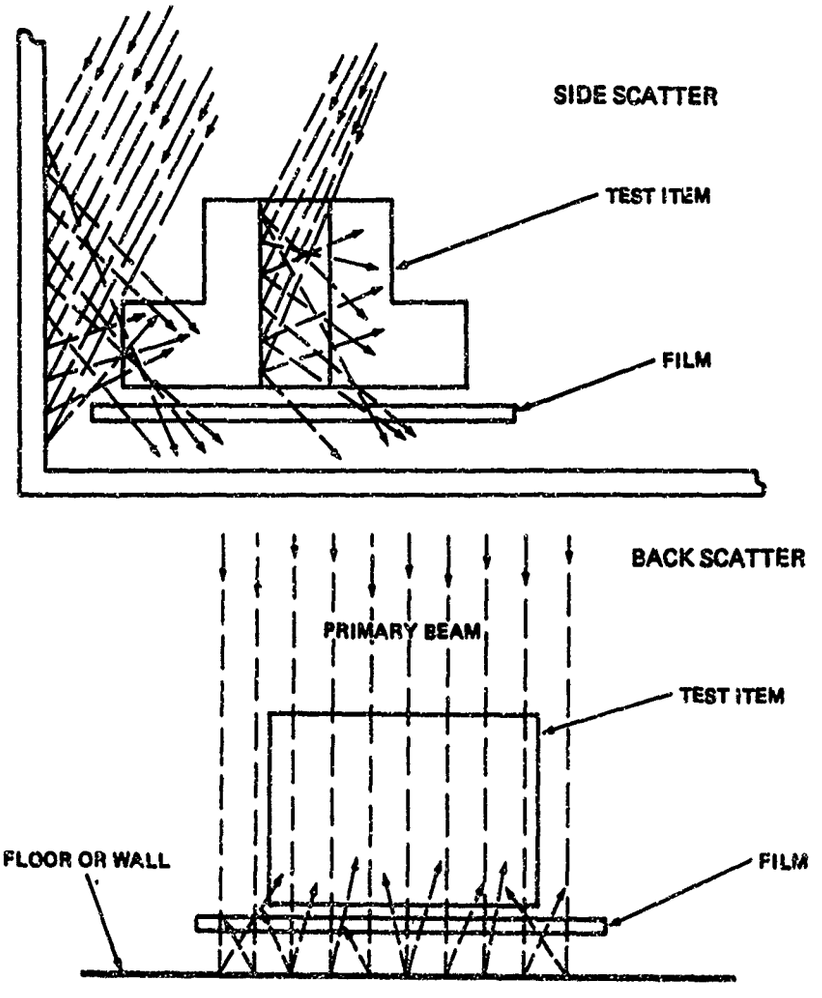


Figure 17. Side and Back Scatter

c. Intensifying Screens. Intensifying screens are often used for radiography at voltages above 100 kv. These filter out much of the low-energy scatter radiation. They are generally fabricated from lead sheets 0.005 or 0.010 inch thick. Under action of X- or gamma-rays above approximately 88 kv, the lead screen also emits electrons. When in intimate contact with the film, these electrons produce additional coherent darkening of the film. Exposure time can be substantially reduced by use of such intensifying screens on either side of the film.

d. Production and Measurement of X-Ray Images. Since there are a large number and variety of factors which have a bearing on the production and measurement of X-ray images, operating factors are generally selected from reference tables or graphs that have been established through empirical methods. An important aspect of producing good radiographs is the knowledge of X-ray films and their processing. The next paragraph in this discussion will describe some of the more important film characteristics and considerations.

25. RADIOGRAPHIC FILM AND PROCESSING

a. General. There are many details a trained radiographer needs to know about radiographic films. Only some of the more general principles can be covered here. For more detail, DOD(I&L) Quality and Raliability Assurance Handbook H 55 on "Radiography" should be consulted. This handbook is listed in the DODISS and is available from the Naval Publications and Form Center, 5801 Tabor Avenue, Philadelphia, Pa. 19120.

To provide a basic understanding of the process involved in the production of an image on X-ray film, it is first necessary to describe what an X-ray film is and what effect radiation and subsequent processing has on it.

An X-ray film is basically a sheet of transparent, blue-tinted, cellulose derivative material, coated on either one or both sides with an emulsion consisting of gelatin that contains dispersed very fine grains of silver halide salts (primarily, silver bromide). The emulsion is about 0.001-inch thick on either side of the film.

The emulsion is sensitive to certain wavelengths of electromagnetic radiation and when exposed to X-, gamma, or visible light rays, a change occurs in its physical structure. This change is of such a nature that it cannot be detected by ordinary physical methods. When the silver halide grains are exposed to radiation, they become "sensitized." When they are subsequently treated with a chemical solution (developer), a reaction takes place causing the reduction of the silver salts to black, metallic silver. It is this silver, suspended in the gelatin, which constitutes the image. The developing solution is basically a mild alkaline reducing solution containing several additional chemicals to control the speed with which the solution acts and to extend the life of the solution. The film is left in the developer long enough to allow the sensitized grains to be darkened; i.e., reduced to metallic silver. If the film is developed too long, unexposed grains will also be reduced, and the film will be uniformly

darkened or fogged. After the film has been developed, it is placed in a weak acid solution to stop the action of the developing solution. The film is then placed in a fixing bath, commonly called a hypo, which dissolves all the undeveloped salts and leaves only the metallic silver or dark grains in the emulsion. This hypo also contains agents which harden the emulsion to make it more durable. Finally, the film is thoroughly rinsed in running water, to remove all traces of the various solutions, and dried. When the processed film is viewed in front of a strong light, those areas of the film which were not exposed to light, X-, or gamma-rays are transparent, while the areas exposed contain metallic silver and are dark or opaque.

X-ray film is very similar to ordinary photographic film except that it is especially sensitive to X- and gamma-rays. Passable photographs can be made with radiographic film, and photographic film will record an inferior radiographic image. Most radiographic films have a response to visible light similar to that of commercial orthochromatic photographic films. Such films are quite sensitive to blue light, but are relatively insensitive to red or yellow light. For this reason, films may be handled in a dark room which is properly illuminated with red or yellow safelights of low intensity. Several types of such lights are commercially available with special filters for use in the processing of radiographic film.

b. Commercial Films. While a photographic image may be formed by light and other forms of radiation, as well as by X- or gamma-rays, the properties of the latter two are of a distinct character and, for this reason, the photosensitive emulsion must be different from that used in other types of photography. In fact, the wide range of conditions and the variety of materials encountered in industrial radiography has led to the development of several specific types of films to meet these diverse requirements.

There are many factors governing the selection of a particular type, or combinations of types of film. Basically, however, there are three grades of film for industrial radiography: coarse grain, fine grain, and extra-fine grain film. The fine and extra-fine grain film give the highest contrast or quality, but require relatively long exposure times. The coarser grain films do not quite give the good quality results that the finer grain films do, but they need only relatively short exposure times. A consideration of all the factors involved in radiographing a given item or component determines the choice of film to be used. Since there is a wide variety of films to choose from, the experienced radiographer is able to select the optimum film for a given job.

Commercial radiographic film is sold in two basic forms. The first is sheet film of various standard dimensions which may be coated with the photosensitive emulsion on only one side, but which is normally supplied coated on both sides of the film; the second is roll film of various widths and practically unlimited length. This second form is especially useful for radiographing circumferential areas. In addition to these two basic forms, custom tailored shapes can be supplied by most manufacturers on request.

c. Film Exposure Considerations. Industrial radiography has many diverse applications. In each application, there are many considerations in obtaining the best radiographic results. They include, but are not limited to:

(1) The composition, shape, and size of the part being examined, and, in some cases, the weight and physical location as well.

(2) The type of radiation used (whether X-rays from an X-ray machine, or gamma-rays from a radioactive source).

(3) The kilovoltages available with the X-ray equipment, or the quality of the gamma radiation.

(4) The kind of information sought (e.g., overall inspection or critical examination of some especially important portion).

(5) The resulting relative emphasis on definition, contrast, density, and the time required for proper exposure.

All of these factors are important in determining the most effective combination of radiographic technique and film.

d. Film Density Considerations. In radiography, film or photographic density generally refers to the quantitative measure of film blackening, and for radiographic purposes the term "density" alone is generally used. Density is defined as the common logarithm of the ratio of light incident upon one side of a radiograph to the light transmitted through the radiograph. To illustrate: when the silver deposited in the emulsion allows 1/10 of the incident light to pass through the radiograph, the ratio is 10:1. The logarithm of 10 is 1; thus by definition the density is 1. If only 1/100 of the incident light passes through the radiograph, the ratio is 100:1 for which the logarithm and therefore the density is 2. By formula:

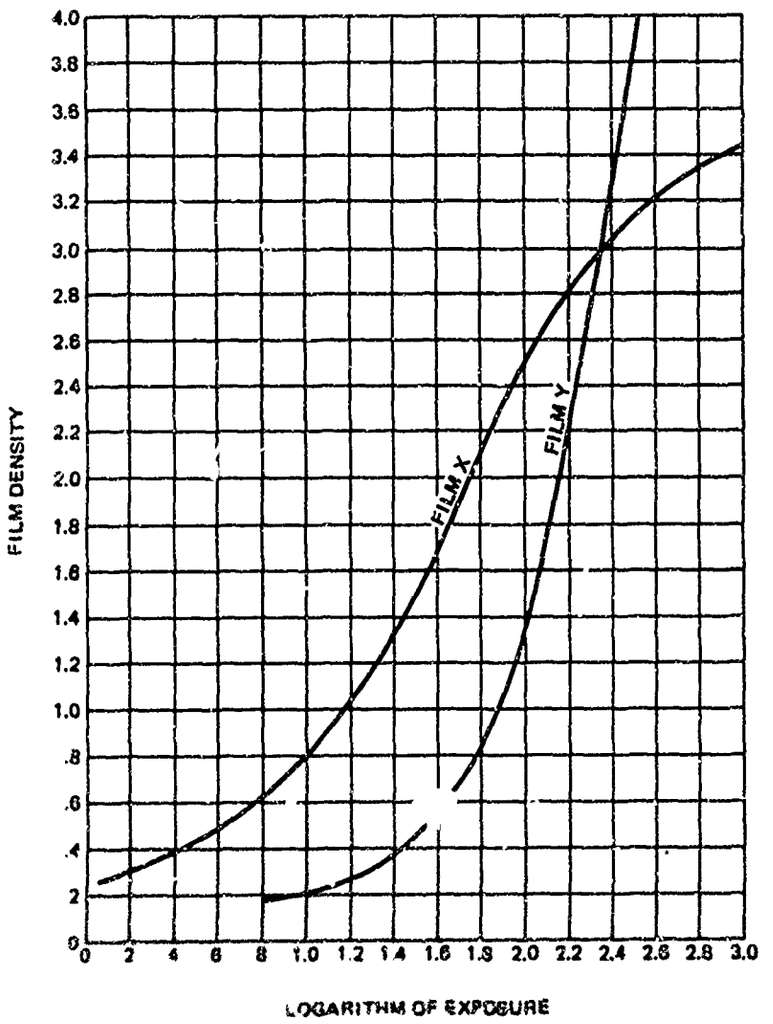
$$\text{Density (D)} = \log \frac{I_o \text{ (incident light)}}{I_t \text{ (transmitted light)}}$$

For general radiographic use, a series of films or a film strip exposed to various density levels is sufficient to compare with and thus judge the approximate density of production radiographs. Density standards of this type should be calibrated using a reliable densitometer. Because the density of a film can vary, the calibration should be made within a small defined area.

e. Film Characteristic Curves. The characteristic curve, sometimes referred to as the sensitometric or H and D curve (after Hurter and Driffield who first used such curves in 1890), expresses the relationship

between the exposure applied to a photographic film and the resulting photographic density. Such curves are obtained by giving a film a series of known exposures, determining the densities produced by such exposures, and then plotting density against the logarithm of relative exposure. Figure 18 shows the characteristic curves of two typical films.

The slope, or steepness of the characteristic curve for radiographic film, changes continuously along its length. The density difference corresponding to a difference in test item thickness depends on the region of the characteristic curve on which the exposures fall. The steeper the slope of the curve in this region, the greater will be the density difference, and hence the greater will be the visibility of detail.



Two Film Types

In general, if th gradient of the characteristic curve is greater than 1.0, the intensity ratios, or subject contrasts, of the radiation emerging from the test item are amplified in the radiographic reproduction, and the higher the gradient, the greater is the degree of amplification. Thus, at densities for which the gradient is greater than 1.0, the film acts as a contrast amplifier. Similarly, if the gradient is less than 1.0, subject contrasts are effectively diminished in the radiographic reproduction.

A minimum density is often specified for radiographs. This is not because of any virtue in a particular density, but rather because of the gradient associated with the density. The minimum useful density is that at which the minimum useful gradient is obtained. In general, gradients lower than 1.0 should be avoided whenever possible.

The ability of a film to amplify the subject contrast is of the utmost importance. Otherwise, many small differences in the subject could not be made visible. This gain in contrast is utilized in practically all industrial radiography. It is especially significant in radiography with very penetrating radiations which produce low subject contrast. High radiographic contrast depends greatly on the enhancement of subject contrast by the film.

It is often useful to have a single number to indicate the contrast property of a film. This need is met by a quantity known as the average gradient, defined as the slope of a straight line joining two points of specified densities on the characteristic curve. In particular, the specified densities between which the straight line is drawn may be the maximum and minimum useful densities under conditions of practical use. The average gradient, then, will indicate the average contrast properties of the film over this useful range. For a given film and development technique, the average gradient will, of course, depend upon the density range chosen. In cases where high-intensity illuminators are available and high densities are used, the average gradient calculated for the density range 1.0 to 4.0 will represent the contrast characteristics fairly well. If high densities are for any reason not to be used, a density range of 0.5 to 2.5 is suitable for evaluation of this quantity. Manufacturers of films generally supply characteristic curves with them.

Experiments have shown that the shape of the characteristic curve is, for practical purposes, independent of the quality of X- or gamma-radiation. Therefore, a characteristic curve made with any radiation may be applied to exposures made with any other, and the same is true of values of gradient or average gradient derived from the curve.

The influence of kilovoltage or gamma ray quality on contrast in the radiograph, therefore, is due primarily to its effect upon the subject contrast, and only very slightly, to any change in the contrast characteristics of the film. Radiographic contrast can also be modified by choice of a film of different contrast, or by use of a different density range with the same film. Contrast can also be affected by the degree of development, but, in industrial radiography, films are developed to their maximum, or

nearly maximum contrast. In the early stages of development, both density and contrast increase quite rapidly with time of development. However, with about 5 minutes development at 68° F (?0° C) in fresh developer or developer plus replenisher, most of the available density and contrast have been attained. With the direct X-ray film types, approximately 30 percent more speed, and in some cases, slightly more contrast can be gained by developing for 8 minutes.

A special case arises when, for technical or economic reasons, there is a maximum allowable exposure; i.e., exposure time cannot be increased to take advantage of the higher film gradient at higher densities. In such a case, an increase in kilovoltage will increase the radiation intensity penetrating the test item, and hence cause the film to be exposed to a higher density. This may result in an increase in radiographic contrast in spite of the lowering of the subject contrast.

It can be seen that, with the exposure time fixed, the density difference between the two sections increases, and hence the visibility of detail in this thickness range is also increased, as the kilovoltage is raised. The increase in visibility of detail occurs in spite of the decrease in subject contrast occasioned by the increase in kilovoltage, and is the direct result of using higher densities, where the film gradient is higher. Qualitatively, the film contrast is decreasing as a result of increased kilovoltage. It should again be emphasized that this change in radiographic contrast with kilovoltage is not the result of a change in characteristic curve shape, but rather the result of using a different portion of the characteristic curve; a portion where the slope is greater.

f. Film Speed. It has been shown that the contrast properties of a film are governed by the shape of the characteristic curve. The other significant value obtained from the characteristic curve is the relative speed, which is governed by the location along the log E axis of the curve in relation to the curves of other films.

Speeds of radiographic films are usually given as inversely proportional to the exposure required to achieve a certain density. Further, since there are no units of radiographic exposure conveniently applicable to industrial radiography, speeds are expressed in terms of one particular film, whose relative speed is arbitrarily assigned a value of 100.

Although the shape of the characteristic curve of a film is practically independent of changes in radiation quality, the location of the curve along the log relative exposure axis, with respect to the curve of another film, does depend on radiation quality.

It has been assumed in the preceding discussions that the exact compensation for a decrease in exposure time could be made by increasing the intensity of the radiation. A radiographer therefore could reduce exposure time by 20 percent if he increased the radiation intensity an equal amount by either shortening the source-film distance or increasing the output of the X-ray source. This direct compensation is termed the reciprocity law and is valid

when using direct X-ray or lead screen exposure techniques. Stated mathematically, for a given exposure (E), the values of intensity (I) and time (t) can be varied at will if their product (I x t) is not changed. The reciprocity law fails when fluorescent screens are used. This failure is due to the radiographic film emulsion which is sensitive not only to the amount but also the brightness of the light. Therefore, when exposure time is increased and radiation intensity decreased, the fluorescent screens will emit the same total amount of light, but over a longer time and at a lower brightness level The effect of this lower brightness will be less exposure to the radiograph. The decrease in film exposure (density) will be small and cause little difficulty until the X-ray intensity is altered considerably. When the X-ray intensity is altered by a factor of 4 or more, it will be necessary to change the total exposure inversely by approximately 20 percent to compensate for this deviation from the reciprocity law.

In radiography, marked changes in an established exposure technique are effected very readily by changing the source-film distance and by taking advantage of the inverse square law effect. When this action is taken and fluorescent screens are being used, the failure of the reciprocity law can be mistaken for a failure of the inverse square law.

g. Technique Charts. Some variables associated with radiography are predictable and can be calculated. One variable, the radiation energy spectrum developed by an X-ray machine, is not readily predictable. Because this spectrum dictates the penetrating quality of the emitted X-rays, the techniques used with any X-ray machine vary and hence require special attention. Such attention usually takes the form of developing data which is pertinent to radiographing various materials and thicknesses of these materials with a particular machine. Such data, when in convenient form, expedites the selection of correct techniques. The general techniques published by X-ray machine vendors are only approximate and seldom satisfactory for direct application.

Industrial radiographic techniques should be based upon the sensitivity required to discern the probable or expected flaws. Because of this fact, technique charts should be designed as plots of either intensity-time or material thickness at a given radiation energy. A radiographer then selects the lowest energy which will provide an economical exposure for a given thickness. The most appropriate manner in which to develop technique charts is outlined as follows:

(1) Subdivide the working range of the X-ray machine into convenient and useful levels determined by the type of work to be accomplished. For example:

> Light alloy radiography with an X-ray machine having a range of 60 to 140 kvp subdivided into five levels; 60-80-100-120-140 kvp.

Steel radiography with an X-ray machine having a range of 50 to 300 kvp, subdivided into six levels; 50-100-150-200-250-300 kvp.

(2) Develop a step-type test item wherein the thickness progresses in increments convenient to the material and process of manufacture to which the intended radiography will apply. For example, when the products of a fabricator vary between 1/8 and 1-1/4 inches in thickness, the step-type specimen would be constructed using 1/8-inch plates. Stacking of plates should allow a sufficient area for each thickness to give a clear image, free of edge effects created by geometric overlay and scattered radiation. Although not necessary, the inclusion of penetrameters on each thickness is helpful in judging final results.

(3) For each of the selected energies, a series of exposures are made using convenient periods of time and the maximum intensity of radiation available from the source. The convenience of the time periods will depend largely upon the type of material involved and the energy of radiation used. The source-subject/subject-film distance (d/t) ratio should be commensurate with good definitive quality and may require change of the distances used (but never the ratio) when the thicknesses involved cover a considerable range. Typical time periods would be minutes (1,2,4,etc.) and seconds (15,30,45 and 60). The magnitude of exposure change should be sufficient to obtain equivalent density on the next greater thickness. The number of exposures made should be confined to reasonable times as would be used in production.

(4) The radiographs obtained will give information regarding exposures of thickness for a given radiation energy, film system, set-up geometry, and material. Each exposure will represent the product of time and intensity of radiation (milli- or microamperes). Each exposure will also illustrate the density range (latitude) which can be expected with the technique used.

(5) The basic information may be modified to suit desired changes in technique without redoing all of the exposures. For example:

The change in exposure required by the use of a different film may be calculated and a second set of exposure values developed and applied to the same graph.

The change in exposure required by a change in d/t ratio can be computed through use of the inverse square law and a second set of exposure values developed for the same curve.

A technique chart for a new alloy (of the same base material) can be developed by making a single exposure at a given thickness and comparing the density thus obtained with the original alloy. The original curve may then be shifted vertically to indicate the technique for the new alloy.

(6) The radiation energy spectrum is a constant for each isotope and for radium. Because of this, only one series of exposures is required to obtain a gamma-ray technique chart for a given material. This series is taken in exactly the same manner as was described for any selected radiation energy. Except for size and radiation intensity, little difference exists between different sources of the same isotope. It is possible, therefore, to apply the same technique charts to any source of the isotope. For this reason technique charts are published and distributed by isotope vendors. These charts are easily modified to be compatible with the user's desired technique.

h. Film Processing and Control. Film is processed so that the latent image produced by exposure to X- or gamma-rays is made visible and permanent. Processing is carried on under subdued light, or a color to which the film is relatively insensitive. The film is first immersed in a developer solution which causes the areas exposed to radiation to become dark, the amount of darkening for a given degree of development depending upon the degree of exposure. After developing, the film is rinsed, preferably in an acid bath. To stop development, the film is next put into a fixing bath, which dissolves the undarkened portions of the sensitive silver salts, and then is washed to remove the fixing chemicals and dissolved salts. Film processing — both automatic and manual — are covered extensively in the literature and in manufacturer's instructions and, therefore, will not be described in detail here.

Defects, spots, and marks of many kinds can occur if correct general processing rules are not carefully followed. Perhaps the most common processing defect is a streakiness or mottle in areas which received a uniform exposure. This unevenness may be a result of:

(1) Failure to agitate the films sufficiently during processing.

(2) The use of too many hangers in a tank resulting in inadequate spacing between films.

(3) Insufficient rinsing between processing steps.

(4) The use of depleted solutions.

Other characteristic marks are: (1) dark spots caused by the spattering of developer solution, static electric discharges, and finger marks; and (2) dark streaks occurring when the developer-saturated film is inspected for a prolonged time before a safelight lamp. When it is possible to avoid it, films should never be examined at length until they have been dried. Fog is an undesirable development of silver salts due to causes other than those affected by radiation during exposure and is a great source of annoyance. It may be caused by accidental exposure to light, X-rays, or radioactive substances; contaminated developer solution; development at too high a temperature; or by keeping films under improper storage conditions or beyond its normal shelf life. A common occurrence is accidental exposure of the film to X-radiation, because of insufficient protection from high-voltage tubes; films have been fogged through 1/8 inch of lead in a room 50 feet or more from the tube.

The location, design, and construction of the X-ray processing facilities are major factors in the installation of adequate radiographic services. The facilities may be a single room, or a series of rooms for individual activities, depending upon the amount and character of the work performed. Because of the special importance of these rooms for the handling, processing, and storing of X-ray films, both their general and detailed features should be carefully planned.

26. GAMMA RADIOGRAPHY

a. General Information. Gamma rays are emitted from the disintegrating nuclei of: (1) natural radiographic elements (such as radium); and (2) from a variety of artificial radioactive isotopes produced in nuclear reactors. Cobalt 60, Iridium 192, Thulium 170, and Cesium 137 are often used for industrial radiography. Isotopes are varieties of the same chemical element having different atomic weights. A parent element and its isotopes all have an identical number of protons in their nuclei but a different number of neutrons. Among the known elements, there are more than 800 isotopes of which more than 500 are radioactive. The wavelength and intensity of gamma waves are determined by the source isotope characteristics, and cannot be controlled or changed. Natural isotopes will be discussed first and then those produced artificially.

b. Natural Isotope Sources. Every element having an atomic number greater than 82 has a nucleus that will probably disintegrate because of its inherent instability. Radium is the best known and most used natural radioactive source and is somewhat typical of all radioactive substances. Radium releases energy in the form of:

(1) Gamma Rays. Short wavelength electromagnetic radiation of nuclear origin.

(2) Alpha Particles. Helium nuclei, consisting of two protons and two neutrons, with a double positive charge.

(3) Beta Particles. Negatively charged particles having mass and charge equal in magnitude to those of the electron.

> Note. The penetrating power of alpha and beta particles is relatively negligible; it is the gamma rays that are of use to the radiographer.

c. Artificial Sources. There are two sources of artificial radioactive isotopes (radioisotopes). The radioisotope used in radiography can be obtained as a byproduct of nuclear fission, e.g., Cesium 137. The second and most common means of creating radioisotopes is by bombarding certain elements with neutrons. The nuclei of the bombarded element are changed, usually by the capture of neutrons, and thereby may become unstable or radioactive. Commonly used radioisotopes obtained by neutron bombardment are Cobalt 60, Thulium 170, and Iridium 192. The numerical

designator of each of these isotopes denotes its mass number and distinguishes it from the parent isotope, and other isotopes of the same element. Artificially produced isotopes emit gamma rays, alpha particles, and beta particles in exactly the same manner that natural isotopes do.

d. Gamma Ray Intensity. Gamma ray intensity is measured in roentgens per hour at one foot (rhf), or a measure of radiation emission over a given period of time at any fixed distance. The activity (amount of radioactive material) of a gamma ray source determines the intensity of its radiation. The activity of artificial radioisotope sources is determined by the effectiveness of the neutron bombardment that created the isotopes. The measure of activity is the curie (3.7×10^{10} disintegrations per second).

e. Specific Activity. Specific activity is defined as the degree of concentration of radioactive material within a gamma ray source. It is usually expressed in terms of curies per gram or curies per cubic centimeter. Two isotope sources of the same material with the same activity (curies) having different specific activities will have different dimensions. The source with the greater specific activity will be the smaller of the two. For radiographic purposes, specific activity is an important measure of radioisotopes, since the smaller the radioactive source the greater the sharpness of the resultant film image.

f. Half Life. The length of time required for the activity of a radioisotope to decay (disintegrate) to one-half of its initial strength is termed "half life." The half life of a radioisotope is a basic characteristic, and is dependent upon the particular isotope of a given element. In radiography, the half life of a gamma ray source is used as a measure of activity in relation to time, and dated decay curves are supplied with radioisotopes when procured.

g. Inverse Square Law. Gamma rays and X-rays have identical propagation characteristics because they both conform to the laws of light. Just as it does with X-rays, the intensity of gamma ray emission varies inversely with the square of the distance from the source.

h. Gamma Ray Quality Characteristics. Radiation from a gamma ray source consists of rays having wavelengths (energy) determined by the nature of the source. Each of the commonly used radioisotopes have specific uses based on their fixed gamma energy characteristics.

27. X- AND GAMMA RADIOGRAPHIC EQUIPMENT

a. Radiographic Equipment. Radiographic equipment as discussed in this chapter is limited to radiation source equipment that generates either X- or gamma-radiation.

(1) The three basic requirements for the generation of X-rays are: a source of free electrons; a means of moving the electrons rapidly

in the desired direction; and a suitable material for the electrons to strike. The design of modern X-ray equipment is a result of refinements in the methods of satisfying these requirements.

The productive portion of an X-ray machine is the tube. The remaining components of an X-ray machine are designed to support the function of the tube, or to meet safety requirements. Associated with the tube is equipment which heats the filament; speeds and controls the resultant free electrons in a beam path to the anode; removes the heat generated by the X-ray generation process; and shields the equipment and surrounding area from unwanted radiation. There are, of course, many variations in the size and shape of X-ray tubeheads. (See Figure 19.)

(2) The direction of useful X-radiation is determined by the target positioning at the tube anode and the placement of lead shielding about the tube. Almost any beam configuration desired can be obtained. (See Figure 20.)

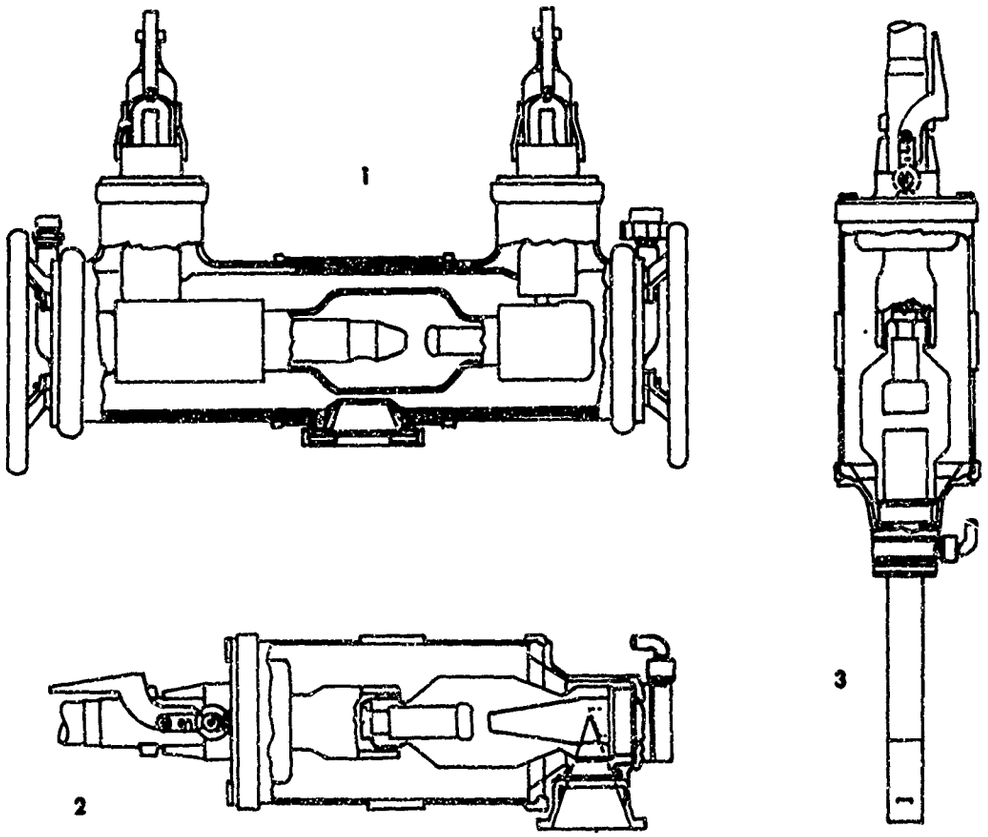


Figure 19. X-Ray Tubeheads

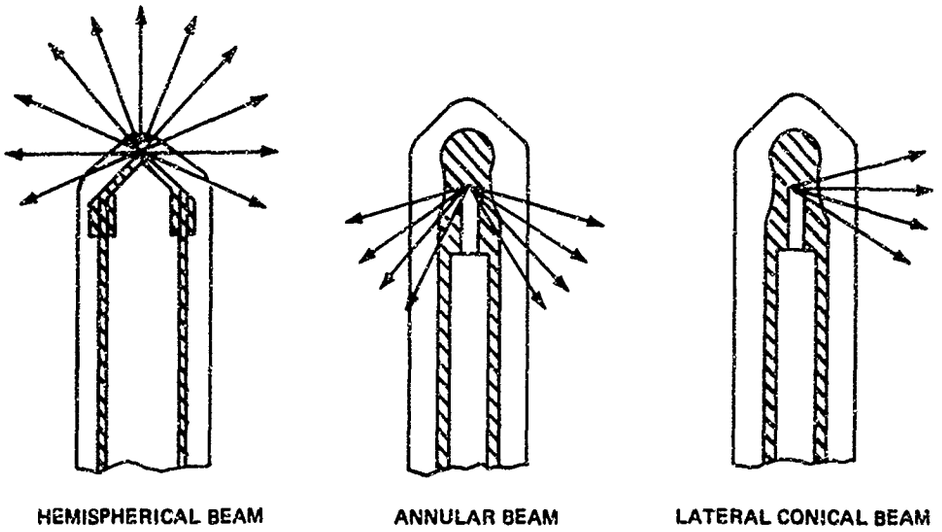


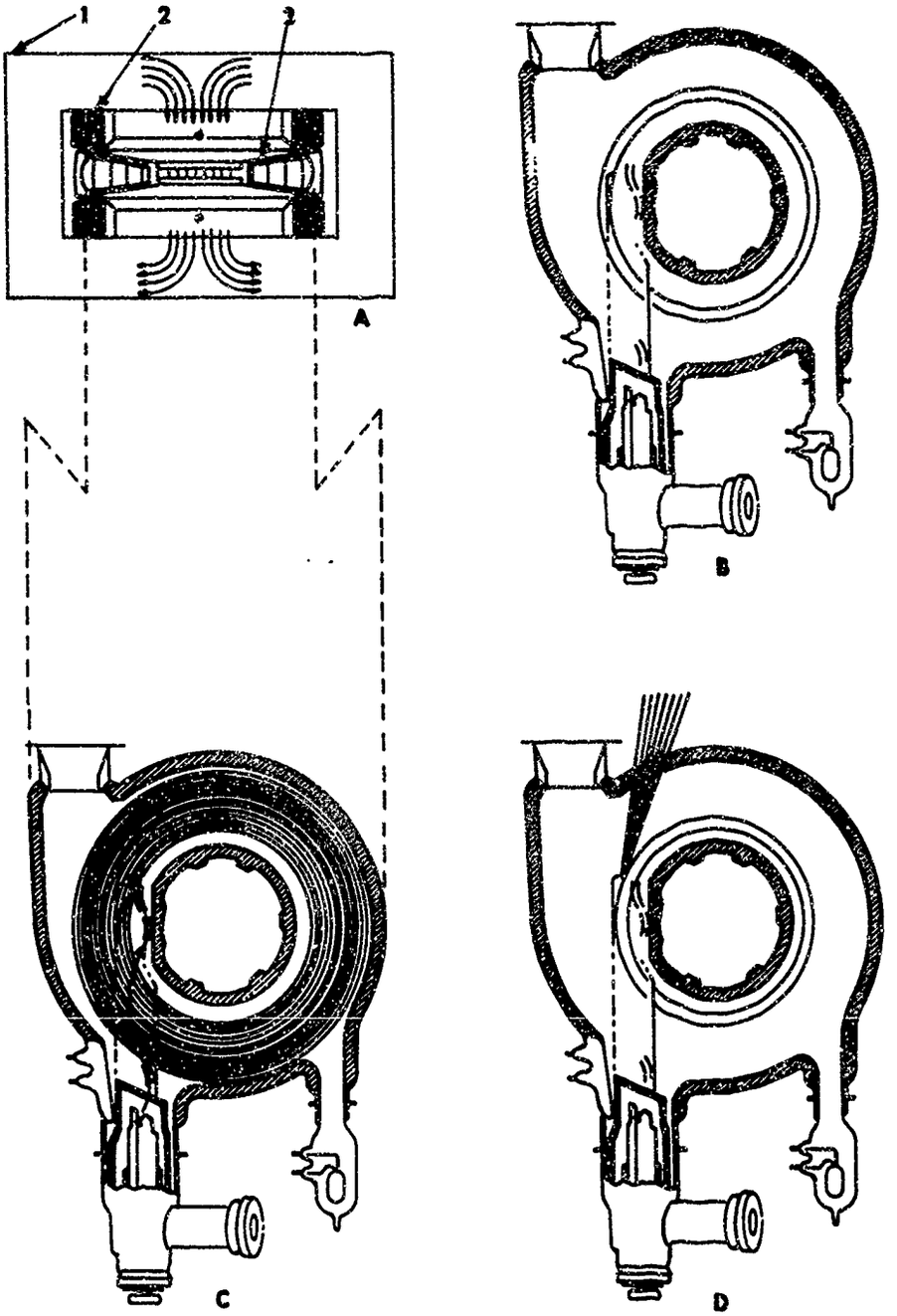
Figure 20. X-Ray Beam Configuration

(3) The operating voltage (difference in electrical potential between the cathode and anode) applied to an X-ray tube determines the penetrating effect of X-radiation. As the voltage is raised, the electron velocity becomes greater and the wavelengths of the generated X-rays become shorter. The high voltage necessary to generate short waves of great penetrating power is obtained from transformers, electrostatic generators, or accelerators.

(a) The majority of X-ray equipment used in industrial radiography uses iron core transformers to produce the required high voltages. Iron core transformers in modern X-ray equipment are either mounted in tubehead tank units with the tube, or are separately housed.

(b) Linear accelerators utilize radio frequency energy in a tuned waveguide to produce an induced field, which is directly related to the length of the waveguide sections, and the radio frequency. The length of a linear accelerator required to obtain electron velocities equivalent to those used in industrial radiography is about six feet.

(c) The betatron accelerates electrons in a circular path by magnetic induction. (See Figure 21.) Its operation is based upon transformer principles since an alternating current applied to the primary (excitation) coil produces a strong variation in the magnetic field in the core of the doughnut shaped secondary. The magnets strengthen this magnetic field. As the magnetic field starts to increase in strength, electrons are injected from a hot cathode injection gun into the "doughnut." The voltage induced by the increasing field causes the electrons to accelerate. The electrons will circle within the doughnut thousands of times



A. CUT THROUGH MAGNET AND ACCELERATOR TUBE
   1. MAGNET
   2. EXCITATION COIL
   3. ACCELERATOR TUBE
B. INJECTION (AND REPLENISHING OF TUBE) OF ELECTRONS
C. CONCENTRATION OF CHARGES ON A NARROW TRACK
D. PRODUCTION OF X-RAYS

Figure 21. Betatron Accelerator

in one cycle of applied voltage, increasing their energy with each rotation. At the moment the magnetic field is at its peak and is about to decrease, a pulse of current is applied to an auxiliary coil which distorts the magnetic field, and ejects the electrons from their circular path. The high energy electrons strike the target and produce X-rays of extremely short wavelength and great penetration power.

(4) The process of X-ray generation is inefficient and most of the energy of the electron beam in the tube is expended in the production of heat. To avoid destruction of the tube anode, this heat must be dissipated. Heat dissipation in medium and low power equipment is usually accomplished through an external finned radiator, which is in good thermal connection with the anode, and is cooled by a flow of oil or gas about its surfaces. Higher power equipment makes use of injection cooling. The coolant, oil or water, is circulated through the hollow anode of the tube. Since the duty cycle (percentage of exposure time versus total time) of X-ray equipment is determined by the rate of anode cooling, the efficiency of equipment cannot exceed the efficiency of its cooling system.

b. Gamma Radiography Equipment.

(1) General. Radiation from radioactive material producing gamma rays cannot be shut off nor can it be directed or controlled. Therefore, gamma ray equipment is designed to provide radiation-safe storage, and remote handling of the radioisotope source. The United States Atomic Energy Commission (USAEC) and various State agencies prescribe safety standards for the storage and handling of radioisotopes under their control. Similar safety procedures are required for the storage and use of radium which is not under USAEC control.

(2) Gamma ray sources. As previously explained, the effective focal spot in X-radiography is the X-ray generating portion of the target. In gamma radiography, since all of the unshielded radioactive material is producing gamma rays, the focal spot is the exposed surface area of the material. The following paragraphs describe some natural and artificial gamma ray sources.

(a) Radium. Radium is a natural radioactive substance having a half life of approximately 1600 years. Because of its slow disintegration, radium is considered in practical applications to have a constant rate of gamma ray emission. Radium itself does not produce useful gamma rays but (through decomposition) produces radon, a radioactive gas with a half life of less than four days, and other radioactive daughter products. It is the disintegration of radon, and the other daughter products, that causes the emission of useful gamma rays. By placing radium in a gas-tight capsule which prevents the escape of radon, a state of equilibrium is reached whereby the amount of radon lost through disintegration is equal to the amount produced by decomposition of the radium. For practical purposes, this state of balance causes a constant rate of gamma ray emission from a radium source. Pure radium is not used in radiography; most sources of this family consist of

radium sulfate packaged in either spherical or cylindrical capsules. Because of its low specific activity, radium is little used in industrial radiography.

(b) Cobalt 60. Cobalt 60 is an artificial isotope created by neutron bombardment of cobalt, having a half-life of 5.3 years. Cobalt 60 primary gamma ray emission consists of 1.33 and 1.17 million electron volts (mev) rays similar in energy content to the putput of a 2 mev X-ray machine. The radioisotope is supplied in the form of a capsuled pellet and may be obtained in different sizes. It is used for radiography of steel, copper, brass and other medium weight metals of thicknesses ranging from 1 to 8 inches. Because of its penetrating radiation, it requires thick shielding with resultant weight and handling difficulty.

(c) Iridium 192. Iridium 192, another artificial isotope produced by neutron bombardment, has a half life of approximately 75 days. It has high specific activity and emits gamma rays of 0.31, 0.47 and 0.60 mev, comparable in penetrating power to those of a 600-kilovolts peak (kvp) X-ray machine. Industrially, it is used for radiography of steel and similar metals of thicknesses between 0.25 and 3.0 inches. Its relatively low energy radiation and its high specific activity combine to make it an easily shielded, strong radiation source of small physical size (focal spot). The radioisotope is obtainable in the form of a capsuled pellet.

(d) Thulium 170. Thulium 170 (obtained by neutron bombardment of thulium) has a half life of approximately 130 days. The disintegration of the isotope produces 84- and 52-kiloelectron volts (kev) gamma rays, soft rays similar to the radiation of X-ray equipment operating in the 50- to 100-kilovolts peak (kvp) range. It is the best isotope known for radiography of thin metals since it is capable of producing good radiographs of steel test items less than one-half-inch thick. One of the major advantages of the use of Thulium 170 is its soft wave radiation, which permits its containment in small equipment units of good portability, since only a small amount of shielding is required. Because the pure metal is difficult to obtain, the isotope is usually supplied in capsules containing the oxide (Tm_2O_3) in powder form.

(e) Cesium 137. Cesium 137 (a by-product of the fission process) has a half life of 30 years. It emits gamma rays of 0.66 mev, equivalent in energy to the radiation of a one mev X-ray machine. It is used in the radiography of steel of thicknesses between 1 and 2.5 inches. It is superior to other isotopes of similar capability only in its slow rate of decay. Cesium 137 is usually handled in the form of the chloride CsCl, a soluble powder requiring special safety precautions. The USAEC recommends double encapsulation in containers constructed of silver-brazed stainless steel.

(f) Other Radioisotopes. Many other radioisotopes that are radiographically useful are not included here because in practical applications one or another of the ones discussed is generally superior.

(3) Isotope Cameras. Because of the ever-present radiation hazard, isotope sources must be handled with extreme care, and stored and locked in adequately shielded containers when not in use. Equipment to accomplish safe handling and storage of isotope sources, together with a source, is called a camera. Figure 22 shows a typical camera. Cameras that use a direct reading of the length of cable extended to indicate source position, and cameras that replace the manual crank with pneumatic or electrical drive units, are only modifications of the basic design. There are, however, other types of cameras that do not require removal of the source from the storage pig. These cameras permit exposure by removal of part of the source shielding.

A typical camera contains the following components:

(a) Shield Case Assembly. A heavy gage steel case containing a block of lead or depleted uranium (storage pig) which shields the source when not in use. Microswitches within the case energize the STORED and OPEN lights which indicate source positions. One end of the case has a connector for the control cable-to-crank extension and the other a connector for the extended source position cable.

(b) Reel Assembly. The reel assembly is comprised of a storage reel for the flexible armored steel cables, a crank to extend and draw back the source, and a light panel housing three control lights. The three lights indicate positions of the source: "STORED" (safely shielded within the pig); "OPEN" (partially extended); and "ON" (fully extended).

(c) Source Switch Assembly. The source switch assembly, located at the extreme end of the extended source position cable, houses the source capsule when it is in the fully extended position. The assembly contains a switch which functions to energize the "ON" control light when the source is in the fully extended position.

(d) Source Capsule Assembly. This is a short length of cable with the source (in a stainless steel container) attached to one end and a connector for attachment to the control cable on the other.

28. SELECTION OF X- AND GAMMA-RAY EQUIPMENT

a. General. Before selecting radiographic equipment for a task it must first be determined that radiography will produce the desired test results. This determination cannot be made until the task has been thoroughly analyzed.

Ideally, there is a best equipment selection for any given radiographic test. Practically, most radiography is accomplished by using immediately available equipment. Such equipment normally lends itself to numerous adaptations and, by careful choice of film and exposure procedures, standard equipment can be used for a variety of tasks. For this reason, the capabilities of individual X-ray machines and isotope cameras overlap in many areas of test. Except in a large production installation or in a

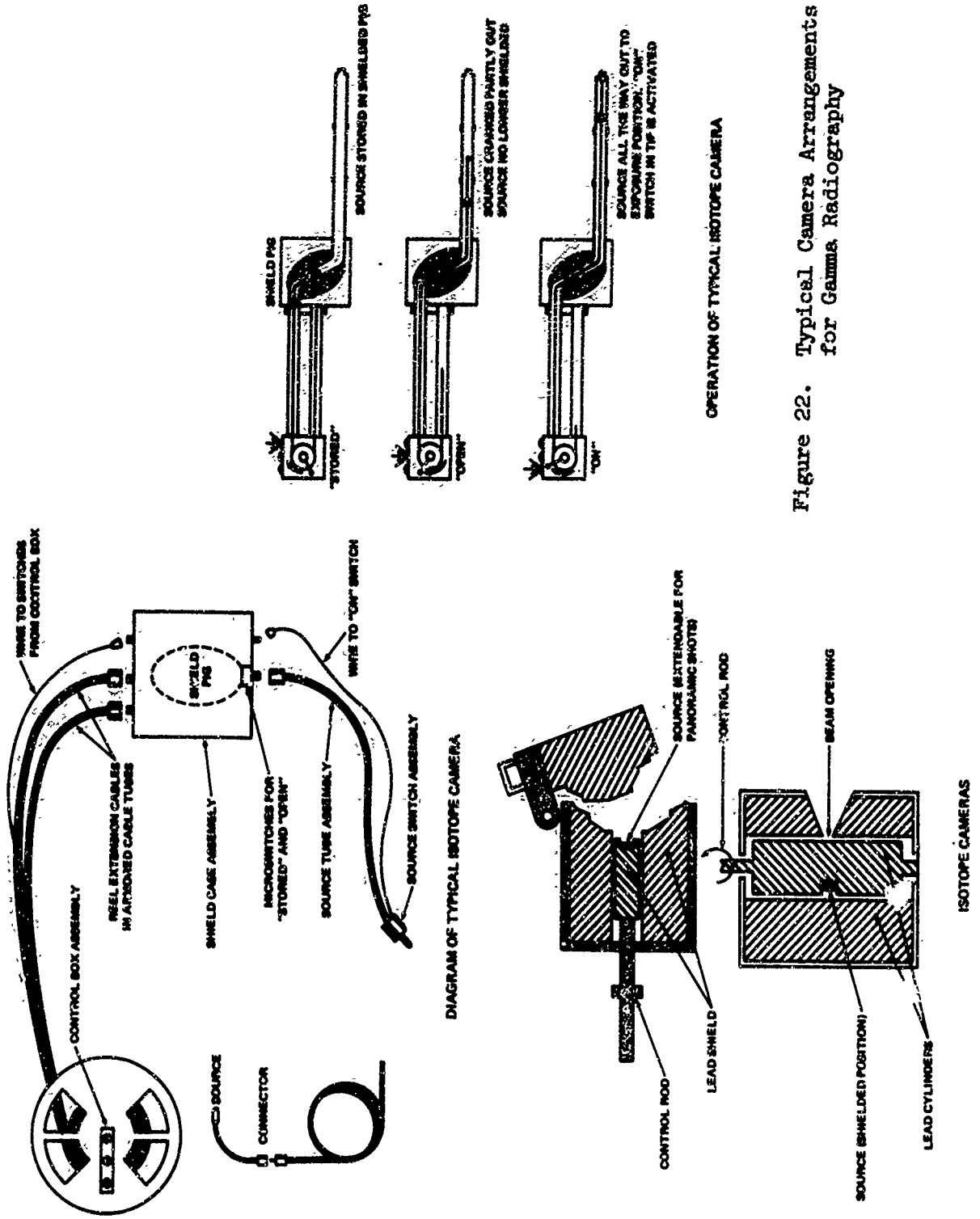


Figure 22. Typical Camera Arrangements for Gamma Radiography

test laboratory, it is impractical to have multiple radiographic equipment. Therefore, it is the responsibility of radiographic test and quality assurance personnel to insure that the equipment and techniques selected are capable of performing the required task.

Because of its flexibility, ease of operation, and fewer radiation hazards, X-radiography is generally preferred to gamma radiography. Gamma radiography is usually selected for industrial applications that involve:

(1) High radiation energy requirements.

(2) Low testing rates.

(3) Simultaneous exposure of many test items.

(4) Confined areas where X-ray equipment cannot be used.

(5) Field inspections in areas where electrical power is difficult to obtain.

(6) Tasks where fast inspection is not required or an important consideration.

b. Factors to Consider and Use of Accessory Equipment. Prior to the selection of specific radiographic equipment for a test, the radiographer must consider all aspects of the job. Available equipment, the time allocated for the test, and the number or frequency of similar items to be tested are major considerations. To create a radiograph, only a radiation source, a test item, and film are needed. To create a useful radiograph of quality, additional equipment is often required. Auxiliary equipment used by the radiographer includes the following items:

(1) Diaphragms, collimators and cones.
(2) Filters.
(3) Screens.
(4) Masking material.
(5) Penetrameters.
(6) Shim stock.
(7) Step wedges.
(8) Film holders and cassettes.
(9) Linear and angular measuring devices.
(10) Positioning devices.
(11) Identification and orientation markers.
(12) Shielding materials.
(13) Densitometers.
(14) X-ray exposure charts.
(15) Gamma ray exposure charts.
(16) Dated decay curves.
(17) Film characteristic curves.
(18) Table of radiographic equivalence factors.

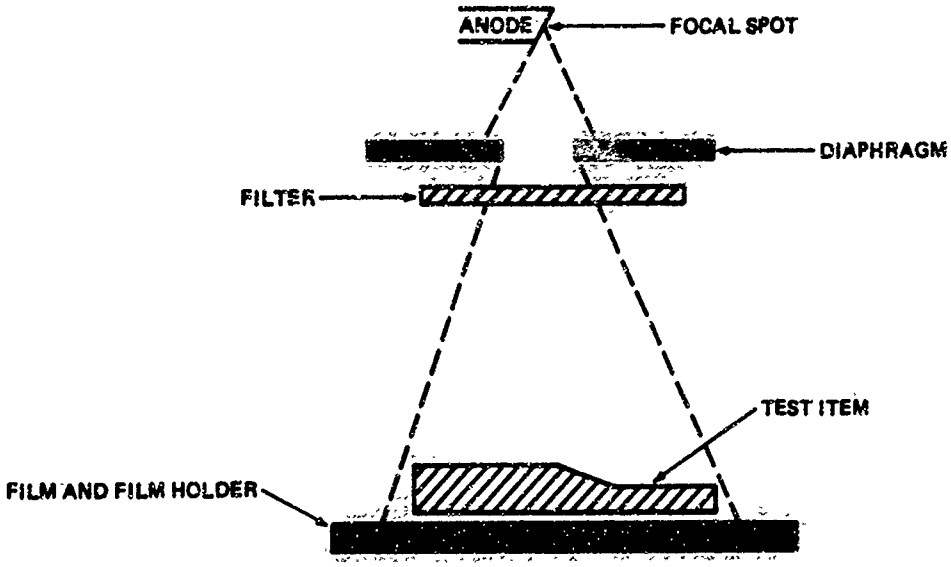
c. Diaphragms, Collimators, and Cones. Diaphragms, collimators, and cones are thicknesses of lead, fitted to the tubehead of X-ray equipment, or built to contain a gamma ray source, and designed to limit the area of radiation. (See Figure 23.) They decrease the amount of scatter radiation by limiting the beam to the desired test item area. Many X-ray machines have built-in adjustable diaphragms designed so that the beam at a fixed distance covers a standard film size area.

d. Filters. Filters are sheets of high atomic number metal, usually brass, copper, steel, or lead, placed in the X-ray beam at the tubehead. (See Figure 23.) By absorbing the "soft" radiation of the beam, filters accomplish two purposes: they reduce subject contrast permitting a wide range of test item thicknesses to be recorded with one exposure; and they eliminate scatter caused by soft radiation. Filters are particularly useful in radiography of items with adjacent thick and thin sections. The material and thickness of the test item, and its range of thicknesses determine the filter action required. No tables of filter thicknesses are available. In radiographing steel, however, good results are usually obtained by using: lead filters 3 percent of the maximum test item thickness; or copper filters 20 percent of the maximum test item thickness. Particular care must be exercised in the use of such filters since defects in the filter may be mistakenly interpreted as test item defects.

e. Screens. When an X- or gamma-ray beam comes in contact with film, less than one percent of the radiation energy available is absorbed by the film in producing an image through photographic effect. To convert the unused energy into a form that can be absorbed by film, fluorescent or lead radiographic screens may be used. The intensification factor of lead screens is much lower than that of fluorescent screens. Under exposure to low radiation, it is possible for the front screen absorption effect to be of such magnitude that required exposure is greater than that without screens. However, because of their capability for reducing the effects of scattered radiation and the resultant better contrast and definition of the radiographic image, lead screens are used wherever practicable. They are used in almost all gamma ray applications.

To insure the intensification action of lead screens, they must be kept free from dirt, grease, and lint since these materials have high electron absorption qualities and can absorb the "intensifying" electrons emitted by the screens. The screens may be cleaned with carbon tetrachloride and, if a more thorough cleaning is desired, fine steel wool may be used. The fine abrasion marks caused by gently rubbing with steel wool leave no harmful effects. Deep scratches, gouges, wrinkles, or depressions that affect the flatness of the screen surface will cause poor radiographic results.

f. Masking Material. Masking is the practice of covering, or surrounding, portions of the test item with highly absorbent material during exposure. Masking reduces the test item exposure in the masked areas, eliminating much scatter. Commonly used masking materials are lead, barium clay, and metallic shot (see Figure 24). When barium clay is used as a mask material, it should be thick enough so that radiation absorption of the clay is appreciably



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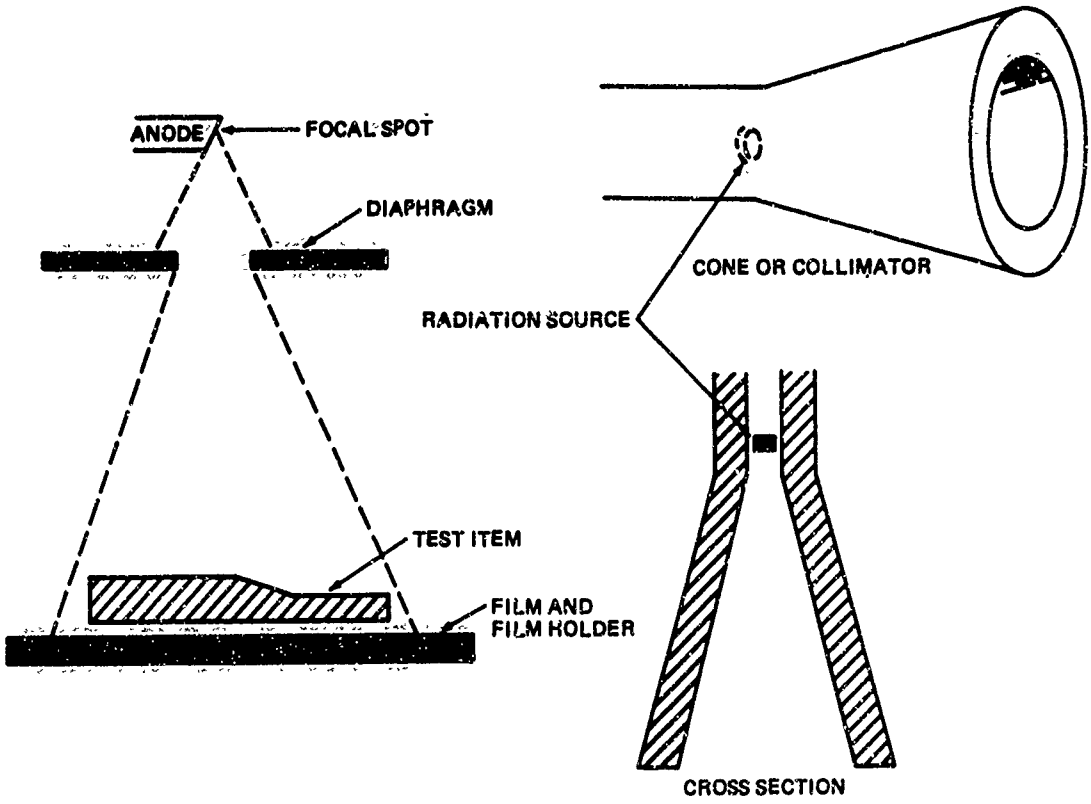
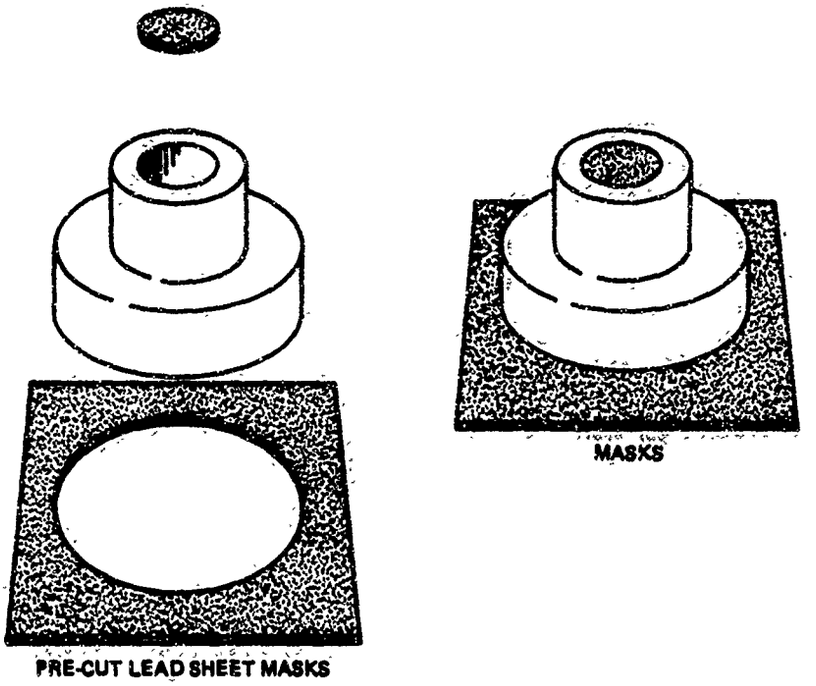
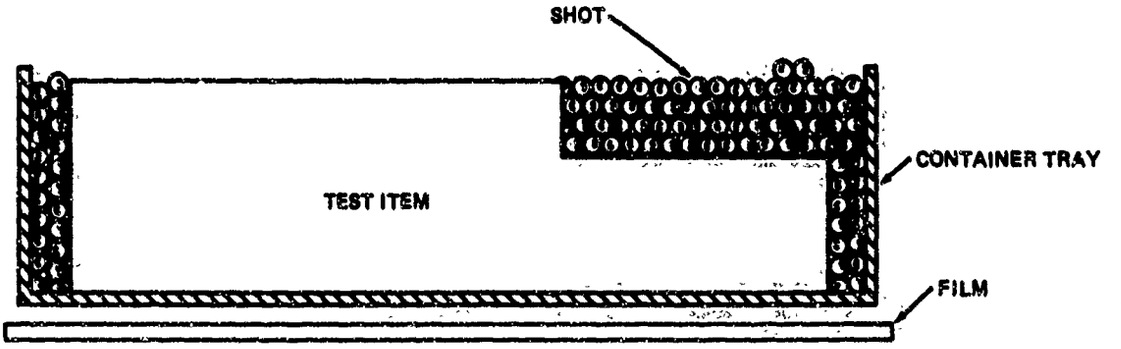


DIAPHRAGM, COLLIMATOR AND CONE

Figure 23. Accessories for Radiographic Testing



LEAD MASKING TECHNIQUE



MASKING WITH METALLIC SHOT

Figure 24. Masking Techniques for Radiography

greater than that of the test item. Otherwise, the clay will generate noticeable scatter. In any circumstance, the sole purpose of masking is to limit scattered radiation by reducing the area of the test item exposed to the primary beam.

g. Penetrameters. The penetrameter, for measuring radiographic quality, is a piece of metal of the same composition as that of the metal being tested, representing a percentage of test item thickness and provided with a combination of steps, holes, or slots. When placed in the path of radiation, its image provides a check on the radiographic technique used. (Figure 25 shows a penetrameter for 1-inch material.)

Penetrameters are used to indicate the contrast and definition which exist in a given radiograph. The type generally used is a small rectangular plate of the same material as the object being X-rayed. It is of uniform thickness (usually 2 percent of the object thickness) and has holes drilled through it. Hole diameters of one, two, and four times the thickness of the penetrameter are specified by ASTM. In addition to the type of penetrameter just described step, wire, and bead penetrameters are also used. These are described in the literature and in ASTM Specification E-94.

The degree of sharpness evidenced by the detail of the outline of the penetrameter is referred to as the contrast sensitivity. If the outline is clearly defined, the contrast sensitivity is referred to as 2 percent or better. Detail is defined as the degree of sharpness of outline of the image. If the radiograph does not show a clear definition of the test item or a flaw in the test item, it is of little value, although it may have adequate contrast and density. Penetrameters of different types have been devised for special uses, e.g., special small wire penetrameters are used in the radiography of small electronic components.

h. Shim Stock. Shim stock for radiographic testing may be defined as thin pieces of material identical to test item material. They are used in radiography of welds, etc., where the area of radiographic interest is thicker than the test item thickness. Shims are selected so that the thickness of the shim equals the thickness added to the test item (by the weld) in the area of interest. (See Figure 26.)

The shim is placed underneath the penetrameter (between the penetrameter and the test item). In this way, the image of a penetrameter is projected through a thickness of material equal to the thickness in the area of interest. In use, the length and width of the shim should always be greater than the similar dimensions of a penetrameter as indicated in Figure 26.

i. Film Holders and Cassettes. Film holders are designed to shield film from light and to protect it from damage. They are made from a variety of materials including rubber and plastic. The holders are flexible and permit molding the film to the contours of the test item, thereby holding item-to-film distance at a minimum. Cassettes are specially designed, usually two-piece hinged, rigid film holders that spring-clamp tightly

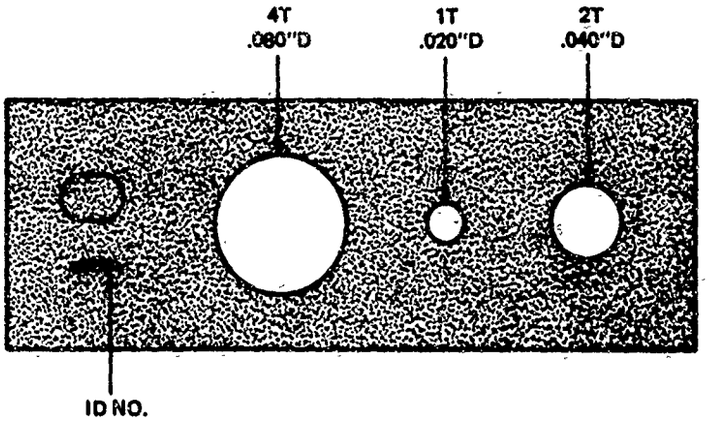


Figure 25. Standard Penetrameter for 1 Inch Material

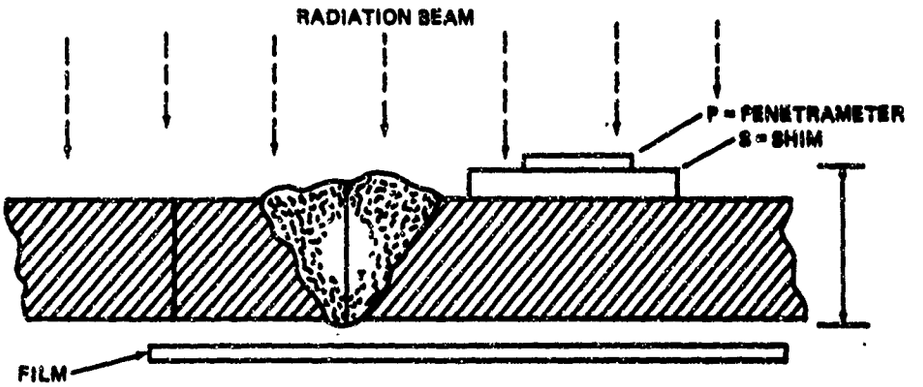


Figure 26. Use of Shim Stock

together. Cassettes are of use when flexibility is not required since their clamping action holds screens and film together, and firmly in place.

j. Linear and Angular Measuring Devices. Correct source-to-film distance and knowledge of test item thicknesses are required for any radiographic setup. For these measurements, a six-inch machinist's scale and a tape measure are often tools of the radiographer. When a task requires radiography at an angle other than that normal to the plane of the test item, a plumb bob and protractor may be used to determine the correct angular setup.

k. Positioning Devices. For quality radiography, the position of the source, the test item, and the film should remain fixed during exposure. For both X- and gamma-ray equipment, the floor, a table, or any stable surface, may suffice to support the test item. Specifically designed holders (usually tripods) are used to position the cable containing the source. Any positioning arrangement complying with safety considerations and not causing excess scatter radiation is generally acceptable.

l. Identification and Orientation Markers. To permit correct interpretation of the finished radiograph, the test item and the radiograph must be marked so that the test item and its orientation can be identified with the radiograph. This may be accomplished by affixing lead numbers or letters to (or adjacent to) the test item during exposure, and marking the test item in identical fashion with a marking pen, or by scribing. The lead numbers or letters, which are attached with masking tape, appear on the radiograph. Comparison of the radiograph with the marked test item eliminates any possibility of wrong identification.

m. Area Shielding Equipment. The control of scatter radiation may be accomplished only by proper use of shielding. Areas in which radiography takes place must be adequately protected against both side and back scatter. In permanent installations, this is accomplished by use of lead shielded rooms or compartments. When permanent installations are not available, lead screens may be placed so that areas reached by the primary radiation are shielded. The area immediately beneath (or behind) the film should always be covered with lead.

n. Densitometer. The densitometer is an instrument used to measure photographic density. Radiographic density is defined as the degree of blackening of a film. Visual and electronic densitometers are commercially available. Accuracy is desirable in a densitometer but consistency is more important. A good densitometer, under similar conditions of use, will give similar readings each time.

o. X-Ray Exposure Charts. X-ray exposure charts show the relationship between material thickness, kilovoltage, and exposure. Each chart applies only to a specific set of conditions: a certain X-ray machine; a certain target-to-film distance; a certain type of film; certain processing conditions; and the density upon which the chart is based. Exposure charts are adequate to determine exposures of test items of uniform thickness, but

should be used only as a guide when radiographing a test item of wide thickness variations. Charts furnished by manufacturers are accurate only within ±10 percent (since no two X-ray machines are identical). For quality radiography, X-ray exposure charts should be based on: (1) the material most often radiographed; (2) the film most commonly used; and (3) an arbitrarily chosen target-to-film distance. These should be prepared for each X-ray machine in use.

Exposure charts can also be prepared to show film latitude (which is defined as the variation in material thickness which can be radiographed with one exposure) while maintaining film density within acceptable limits. These limits are fixed by the lowest and highest densities that are acceptable in the finished radiograph.

p. Gamma Ray Exposure Charts. The variables in gamma radiography are the source strength and the source-to-film distance. These are related on the chart to each of different speed films. By selecting a given film type, the radiographer can determine exposure time for desired image density. Gamma ray exposure charts are similar to X-ray exposure charts, and are adequate to determine exposures of test items of uniform thickness. However, they should be used only as a guide when radiographing a test item of wide thickness variation. Charts are available from film manufacturers and are generally accurate when used with film processed in compliance with the manufacturer's recommendations.

q. Dated Decay Curves. Dated decay curves are supplied with radioisotopes. By use of the curve, the source strength may be determined at any time. Since the source strength must be known before exposure calculations can be made, the decay curve eliminates the necessity of source strength measurement, or calculation, prior to source use. When source strength is known, decay curves are readily prepared by using half life values and plotting the resultant curve on semi-logarithmic paper.

29. X-RAY INTERPRETATION AND SPECIFICATIONS

Specifications for radiography are published by the Government, ASTM, ASME, AWS, and API. ASTM Standards, Part 31, contains 11 standards for use in radiographic testing. A Standard Method for Controlling the Quality of Radiographic Testing (ASTM Designation: E 142-68) is included in the referenced Part 31. For convenience, the definitions provided in E 142-68 are included as follows:

(1) Radiographic Inspection. The use of X-rays or nuclear radiation or both, to detect flaws in material and to present their images on a recording medium.

(2) Recording Medium. A film or detector which converts radiation into a visible image.

(3) Radiograph. A permanent visible image on a recording medium produced by penetrating radiation passing through the material being tested.

(4) Penetrameter. A device employed to obtain evidence on a radiograph that the technique used was satisfactory. It is not intended for use in judging the size of flaws nor for establishing acceptance limits for materials or products.

(5) Source. A machine or radioactive material which emits penetrating radiation.

(6) Source-Film Distance. The distance between the radiation producing area of the source and the film.

30. RADIOGRAPHIC SAFETY

a. General. The dangers connected with exposure of the human body to X- and gamma-rays should be fully understood by any person responsible for the use of radiation equipment. The National Bureau of Standards (NBS) is a good source of information concerning radiation safety. Regulations governing the exposure to radiation are available in the form of AEC Regulations, Title 10, Chapter 1, Part 20. Reference to the current full statement of Part 20 is required for a full understanding of the regulations. A health safety program is usually in effect at all installations where radiography is performed.

The radiographer is cautioned to keep himself aware of the latest effective safety regulations and to become familiar with local health safety programs. Most of the effects of radiation on the human body are known and predictable. Radiation safety practices are based on these effects, and the characteristics of radiation. Since radiation cannot be detected by any of the human senses, and its damaging effects do not become immediately apparent, personal protection is dependent upon detection devices and adequate shielding. The United States Atomic Energy Commission (USAEC) enforces safety regulations covering the handling and use of radioisotopes. The Interstate Commerce Commission, the Civil Aeronautics Board, and the United States Coast Guard enforce safety regulations covering the transportation of radioactive material. The various States have similar regulations covering use, handling, and transportation of radioactive material. All of these regulations are designed to limit radiation exposure to safe levels, and to afford protection for the general public. This Government emphasis on safety practices indicates the mandatory nature of sure and certain safety practices in all radiation areas. The radiographer who is a licensee of the USAEC or who is employed by a licensee must have knowledge of, and comply with, all pertinent regulations. Radiography is safe if all pertinent regulations are known and obeyed.

b. Units of Radiation Dose Measurement. For radiation safety purposes, the cumulative effect upon the human body of radiation exposure is of primary concern. Since the damaging effects of radiation to living cells are dependent upon both the type and the energy of the radiation to which they are exposed, it is impractical to measure radiation only quantitatively. For this reason, exposure is first measured in physical terms. Following this, a factor allowing for the relative biological effects of different types and energies of radiation is applied.

The units used to measure radiation exposure are defined as follows:

(1) Roentgen. The roentgen (r) is the unit measure of X- or gamma radiation in air. It is a physical measurement of X- and gamma radiation quantity. It is defined as the quantity of radiation that will produce one electrostatic unit (esu) of charge in one cubic centimeter of air at standard pressure and temperature. One roentgen of radiation represents the absorption of ionization of approximately 83 ergs of radiation energy per gram of air. In practical application, the milliroentgen (mr), one thousandth of a roentgen, is often used.

(2) Rem. The roentgen is a measurement in air only and the rem (roentgen equivalent man) is the unit used to define the biological effect of radiation on man. It represents the absorbed dose in rads multiplied by the relative biological effectiveness of the radiation absorbed.

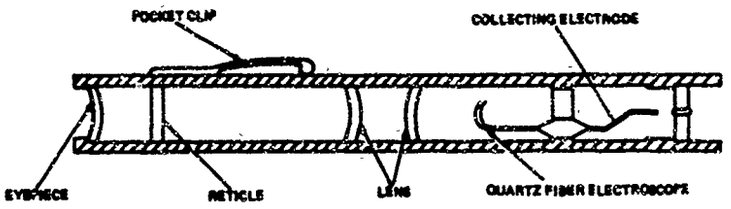
(3) Rad. The rad (radiation absorbed dose) is the unit of measurement of radiation absorption by humans. It represents an absorption of 100 ergs of energy per gram of irradiated material, at the place of exposure. The roentgen applies only to X- and gamma rays. The rad applies to any type of radiation.

(4) Rbe. The value assigned to various types of radiation, determined by the radiation's effect on the human body, is called rbe (relative biological effectiveness). Practically, the dose in rem is the product of the rad and rbe.

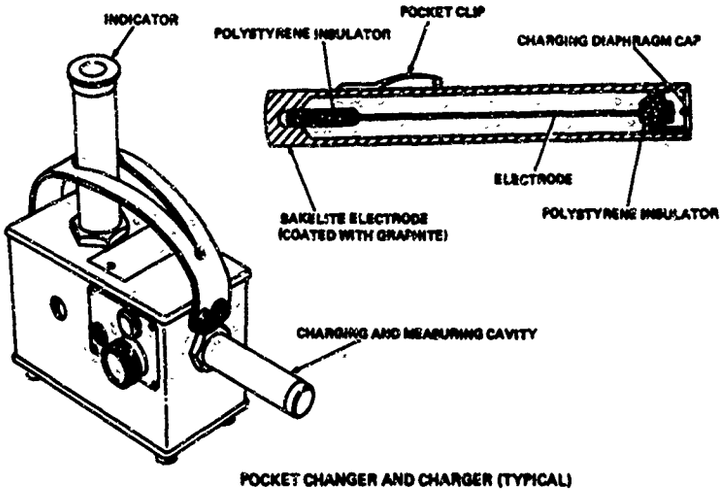
Radiation safety levels are established in terms of rem dose. The calculating of rem dose of X- and gamma radiation is simplified by two facts, (1) the roentgen dose is equivalent to the rad dose, and (2) the rbe of both X- and gamma radiation is one. A measurement of roentgen dose thus becomes a measurement of rem dose.

c. Radiation Detection and Measurement Instruments. A physical radiation survey should be made to determine that each sealed source is in its shielded condition prior to securing the radiographic exposure device and storage container.

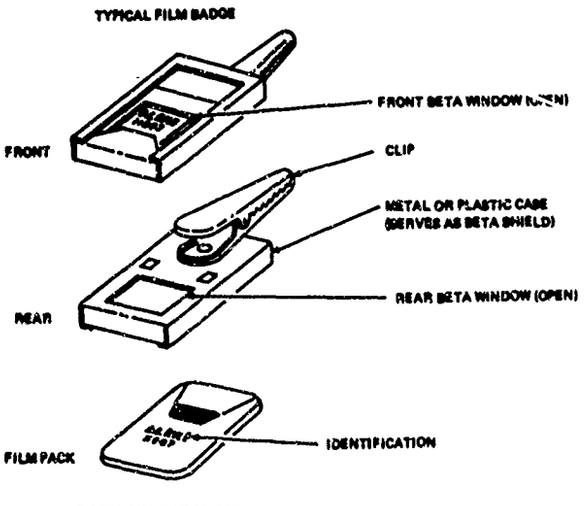
Various techniques, based on the characteristic effects of radiant energy on matter, are employed in detection and measurement devices. Chemical and photographic detection methods are used, as well as methods which measure the excitation effect of radiation on certain materials. In radiography, however, the instruments most commonly used for radiation detection and measurement rely on the ionization produced in a gas by radiation. Since the hazard of radiation is calculated in terms of total dose and dose rate, the instruments used for detection and measurement logically fall into two categories: instruments that measure total dose exposure, such as pocket dosimeters, pocket chambers, and film badges; and instruments that measure dose rate (radiation intensity), such as ionization chambers and Geiger counters. These instruments are known as survey meters. (See Figure 27.)



POCKET DOSIMETER (TYPICAL)



POCKET CHANGER AND CHARGER (TYPICAL)



FILM BADGE (TYPICAL)

Figure 27. Radiation Exposure Equipment

31. ELECTRICAL SAFETY

The radiographer must comply with safe electrical procedures when working with X-ray equipment. Modern X-ray machines use high voltage circuits. Permanently installed X-ray facilities are designed so that personnel trained in safe practices will encounter little electrical hazard. However, portable X-ray equipment requires certain electrical precautions.

Whenever X-ray equipment is being operated or serviced, the following precautions, applicable to both permanent and portable installations, should be observed:

(1) Do not turn power on until setup for exposure is completed.

(2) Insure that grounding instructions are carefully followed.

(3) Regularly check power cables for signs of wear and replace immediately when needed.

(4) Avoid handling power cables when power is ON.

32. RADIOGRAPHY ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Highly sensitive to changes in density and thickness of the test object.

(2) Provide good definitions of flaws.

(3) Provide a permanent record.

(4) Equipment, accessories, and films are commercially available.

(5) Industrial and military experience provide evidence of reliability and capability for interpretation of X-ray images of well known materials.

b. Disadvantages.

(1) Expensive due to the price of equipment, film, and processing.

(2) Unless a process such as self-processing film development is used, film radiography can require an excessive amount of time.

(3) Radiographs should be interpreted by trained and experienced persons.

(4) Film records are bulky, expensive to store, and expensive to recover for later reference.

Section VI. FLUOROSCOPIC AND ELECTRONIC X-RAY AND GAMMA RAY IMAGING SYSTEMS

33. FLUOROSCOPIC AND TELEVISION IMAGING SYSTEMS

a. Fluoroscopy. The fluoroscopic imaging system shown in Figure 28 essentially substitutes a fluorescent screen for the film used in conventional (film) radiography. The X-ray image is produced directly on the fluorescent screen, and is viewed indirectly through an optical system to prevent direct eye exposure to hazardous radiation. It is a relatively low-cost, high-speed process and is easily adapted to production line requirements. It is widely used in applications where rapid scanning of articles for gross internal flaws or abnormal conditions is desirable. By use of fluoroscopy, a large number of articles can be screened prior to radiographic test. Those with gross defects are immediately rejected, with resultant cost savings. Fluoroscopy cannot be used with test items that are thick or of dense material since the intensity of the radiation passing through the test item would be too low to brighten the screen sufficiently for viewing. In using fluoroscopy, an image amplifier is employed to enhance the brightness of the image. This image amplifier also serves to protect the operator from radiation. It consists of an image tube and an optical system. The image tube converts the X-ray image on the fluorescent screen to electrons, and it accelerates and electrostatically focuses the electrons to produce the image on the smaller fluorescent screen. The optical system magnifies the image.

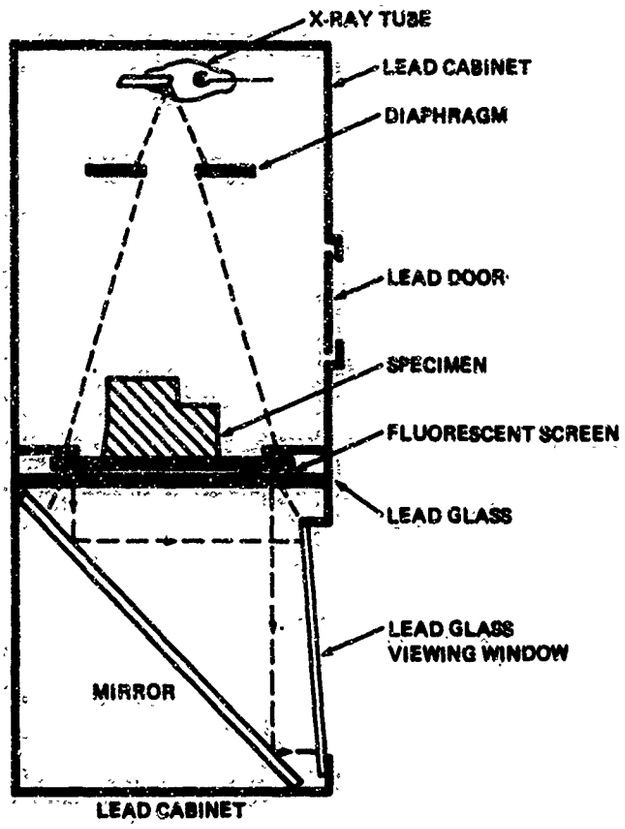
b. Television Imaging. Advanced radiographic techniques are available which allow viewing radiographic images as television pictures. The Vidicon X-Ray System shown in Figure 29 is typical of those using such techniques. Here, a special vidicon television pickup tube is used in the place of the film in conventional (film) radiography; associated circuitry and controls allow the X-ray image to be displayed directly on a television monitor screen. The tube differs from normal vidicon tubes in that it is X-ray sensitive rather than photo-sensitive. It is widely used to permit instant image reproduction, combined with observer protection from exposure. The tube is the key part of the system. Other parts include an X-ray source which provides an intense small-diameter beam, a unit for handling and positioning test items, and a closed circuit television readout. The system is designed for radiographic inspection of small items such as electronic components and assemblies, and system components. It is highly suitable for in-motion X-ray inspection. Permanent records may be obtained by photographing the monitor screen of the readout system.

34. ADVANTAGES AND DISADVANTAGES OF IMAGING TECHNIQUES

a. Advantages.

(1) There is no delay in obtaining the image.

(2) Fluoroscopic and electronic X-ray imaging systems can be used for in-motion imaging of test objects.



SCHEMATIC DIAGRAM OF A FLUOROSCOPE

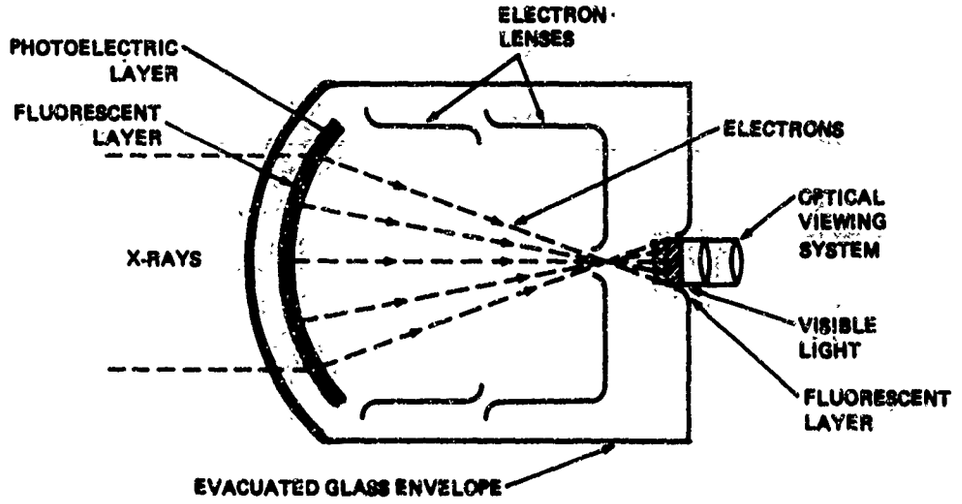


IMAGE AMPLIFIER

Figure 28. Fluoroscopy Equipment

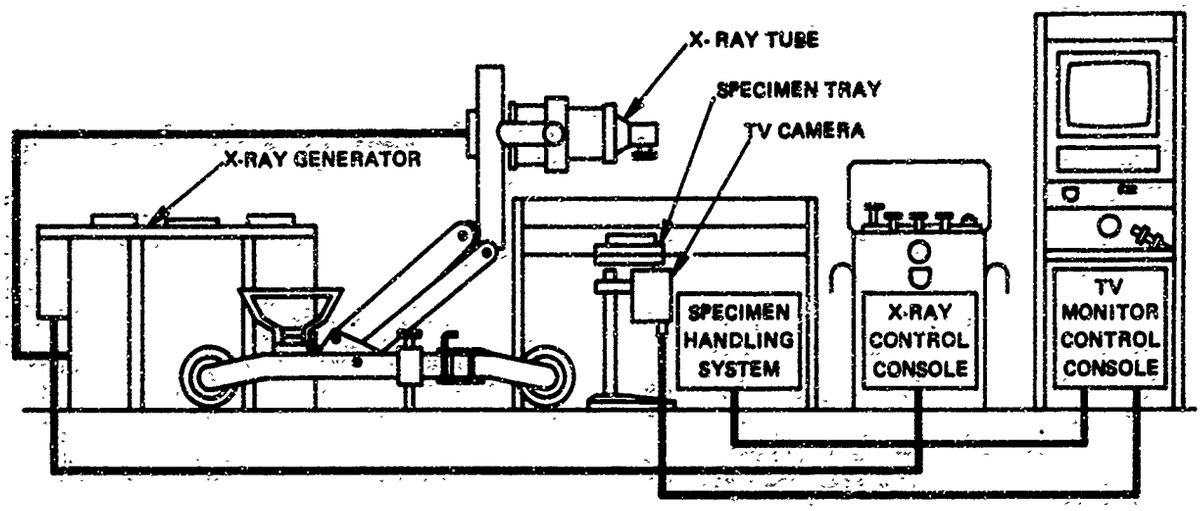


Figure 29. Typical Vidicon X-Ray System

(3) Television-type systems are applicable to remote monitoring, thus enabling the observer to be out of range of hazardous radiation.

(4) Cost of film processing and identification of areas of test objects being radiographed are eliminated by fluoroscopic and electronic imaging systems.

(5) Electronic X-ray imaging is applicable to continuous X-ray inspection to observe process operations and details.

b. Disadvantages.

(1) Clamps, fixtures, other supports, and obstacles must be kept clear of the path of the radiation from the X-ray and gamma-ray source to the radiation sensor.

(2) Less sensitive than film radiography.

(3) Radiation shielding might be a problem for certain applications.

35. SPECIAL RADIOGRAPHIC TECHNIQUES

a. General. A radiographic image has length and width but does not have perspective. When it is necessary to know the depth of a flaw in a thick test item, several special techniques may be used.

b. Stereoradiography. Stereoradiography gives the viewer a three-dimensional effect by use of two radiographs of the test item viewed by means of a stereoscope. (See Figure 30.) The two radiographs are made with the X-ray tube in two different positions relative to the test item. The two positions are displaced from each other by a distance equal to the separation of a human's eyes. The stereoscope, through optical means, permits the viewer to view the two radiographs simultaneously while allowing each eye of the viewer to see only one of the radiographs. The right eye sees the image of the right shift position of the X-ray tube, and the left eye sees the image of the left shift position. The brain combines and merges the two images into one in which true perspective, and spatial relationships are apparent. Stereoradiography is little used in industrial radiography but is of value in flaw location or structural visualization.

c. Double Exposure (Parallax) Method. Double exposure (parallax) techiques are used to quantitatively measure flaw depth in a test item. Figure 31 illustrates the essential features of the method. Lead markers (M_1 and M_2) are fastened to the front and back of the specimen. Two exposures are made with the X-ray tube (at a constant vertical distance (t) from the front surface of the item) being moved parallel to the item surface a known distance (a) from the first to the second exposure positions (F_1 and F_2). The relative positions of the back surface marker (M_2) images will change very little from the first exposure to the second; but, the relative positions of the shadows of the flaw and front surface marker (M_2) will change significantly. Both exposures can be made on the same film, or two separate films can be used, one for each exposure, and the images superimposed one on the other using the back surface markers as reference. The depth of the flaw can then be computed using the expression: $d = bt/(a+b)$.

d. Flash Radiography. Flash radiography permits the observation of high-speed events in opaque materials. It is used primarily for observation of an explosive or rupture processes. Flash radiography "freezes" the motion of projectiles, high-speed machinery, etc., by use of high voltage, high current, and extremely short time duration exposures. The tube and high voltage circuits of flash radiography equipment differ in design from conventional X-ray equipment. The tube has a cold cathode, and electron emission is initiated by a third electrode located near the cathode. The high voltage circuit contains capacitors which are charged to peak voltage and then discharged in a high-voltage pulse. Tube current reaches as high as 2000 amperes but, because of the fractional microsecond duration of the exposure, the tube is not damaged.

e. In-Motion Radiography. In-motion radiography is any radiographic method wherein the source of radiation, the test item, or the film, is moving during the exposure. Many special in-motion radiographic techniques are in use, each of them designed to serve a specific purpose and application. These techniques use mechanical arrangements to move the X-ray machine, the test item, or, in many cases, motion picture cameras loaded with X-ray film. One requirement for in-motion radiography is that during exposure the position of the film and the test item relative to each other must remain fixed.

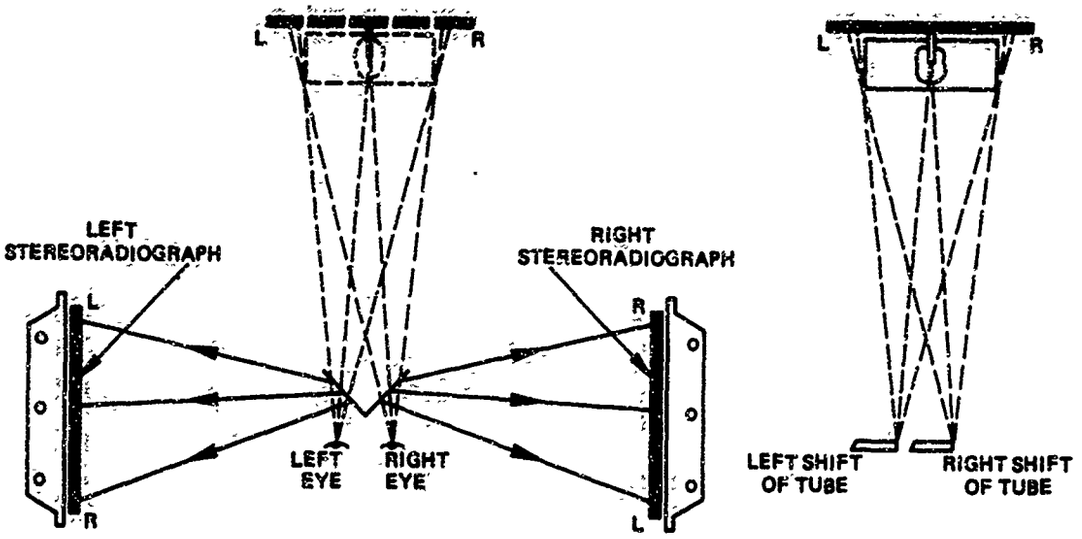


Figure 30. Stereoscopic Radiography

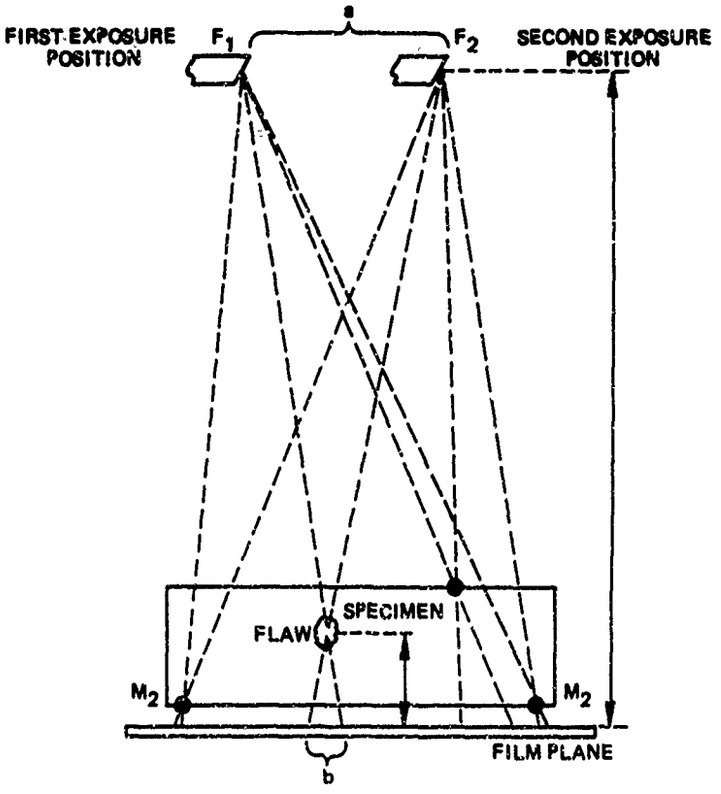


Figure 31. Parallax Technique

This requirement is met by synchronizing the movement of the test item and the film, or by fixing the item and film in position and moving only the source of radiation.

f. Xeroradiography.

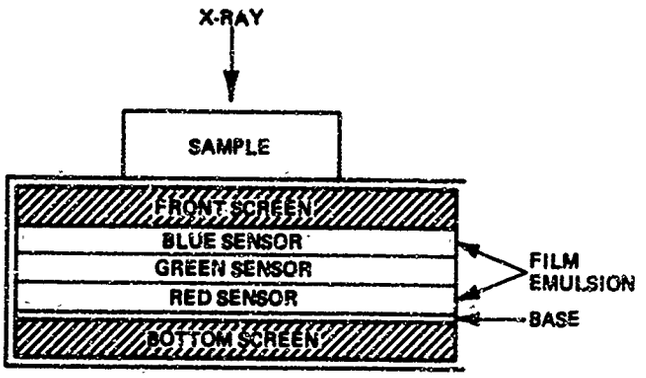
(1) General. Xeroradiography is a "dry" radiographic process that uses electrostatically charged plates to record an X-ray image. The basis of the process is the peculiar characteristic of selenium which causes it to become a relatively good electrical conductor when exposed to X-rays. The plate used to record the X-ray image consists of a thin layer of selenium bonded to a backing plate of aluminum. Under darkroom conditions an electrostatic charge is placed on the selenium by passing a high potential charging bar across the surface of the plate at a uniform velocity. The selenium (because it has good insulation properties) will retain the charge. The sensitized (charged) plate is then placed in a light-tight cassette, or holder, and used in X-ray exposures in the same way as film.

(2) Exposure. When the selenium is exposed, the X-rays cause the insulating properties of the selenium to break down and the charge leaks through (discharges) to the backing plate. Since the amount of discharge is determined by X-ray intensity, an image of the test item remains on the plate in the form of areas that are charged and discharged (in various degrees). The plate is developed after exposure by spraying it with light colored, sometimes fluorescent, finely divided charged powders, which cling to the charged areas in amounts determined by the degree of charge. The powder coating thus visually presents the X-ray image.

(3) Transfer Process. If a permanent record is desired of a xeroradiograph, the image may be photographed or transferred to a special adhesive white paper. The transfer process uses paper coated with a plastic adhesive. When the paper is pressed on the xeroradiograph, it lifts the powder image from the selenium plate. The image is permanently affixed to the paper by applying sufficient heat to soften and bond the plastic coating to the paper.

g. Color Radiography. Some effort has been performed in the color radiography field for years. The colors obtained in the work so far, however, are often not intended to display "true colors" of an object as seen by reflected visible light. Techniques of color radiography have involved such means as three-emulsion color films and lead screens. (See Figure 32.)

When objects which contain a large thickness range must be examined radiographically, a color radiograph will probably supply more information than a black-and-white radiograph made with conventional high-contrast radiographic film. It is possible on high latitude subjects (i.e., mechanisms, circuit boards, welds of two objects varying greatly in thickness) to obtain a fair amount of detail resolution throughout a large thickness range because of the hue and saturation data available from color radiography. Black-and-white radiography of similar objects would require several different exposures to cover the same range of thicknesses.



CROSS-SECTIONAL VIEW OF THREE-EMULSION COLOR FILM, LEAD SCREENS, AND SAMPLE

Figure 32. Cross-Sectional View of Three Emulsion Color Film, Lead Screens, and Sample

At present, the contrast sensitivity obtained with color radiographs is not as good as that often attainable with a high quality black-and-white radiograph. This is partially because the color films now available have been designed for photography. Development of new films and techniques could make color radiography more effective in the near future.

Section VII. SONIC AND ULTRASONIC NDT

36. BACKGROUND

a. General. Ultrasonics probably began as a technology during World War I when piezoelectric crystals were used (in sonar) in early attempts to detect submarines. It was further developed during World War II when pulse echo techniques were developed and low-frequency sonar was used. In the early 1940's, Dr. F. A. Firestone in this country and D. A. Sproule in England produced ultrasonic pulse echo flaw detection instruments. The Firestone instrument was known as the reflectoscope. W. C. Hitt and D. C. Erdman are generally credited with the first practical immersion-type ultrasonic test system and with basic reference standards for use in calibrating equipment and interpreting indications.

Because of the sensitivity of ultrasonics, especially in detecting small cracks, the method is now widely used and accepted. A considerable amount of both stationary and portable equipment is available commercially. In addition to a wide range of equipment, there are numerous techniques and variations of techniques available in the realm of sonic and ultrasonic testing. These are thoroughly described in the literature. Only highlights can be covered here.

b. Sonic NDT. In sonic testing, natural energy can be supplied by the part itself in response to a mechanical impact. Alternatively, forced vibration can supply energy to the test item by one of three electromechanical effects: (1) direct-coupled magnetostriction, (2) direct-coupled piezoelectric crystals, and (3) both effects coupled indirectly. Resulting vibrations are sensed by the reverse operation of the effects just stated. A graphic display of frequencies and relative amplitudes can be plotted or photographed. Detailed vibration information is often required, such as: (1) the frequency (Hertz); (2) amplitude (decibels); and (3) the damping factor.

The sonic technique of testing is used primarily as a laboratory technique where it can be used to detect large cracks and voids, evenly dispersed microcracks and voids, improper plastic cure, evenly dispersed foreign material, and dimensional accuracy.

c. Ultrasonic NDT. Ultrasonics, by definition, describes sound waves too high in frequency to be heard by the human ear. This is generally considered to be approximately 20,000 Hertz. Ultrasonic testing usually employs mechanical vibrations at ultrasonic frequencies from 0.1 to 25 megahertz (MHz).

The type of transmitter/receiver used for ultrasonic testing is usually an electromechanical (piezoelectric) transducer, i.e., a device which converts mechanical energy into electrical energy and vice versa. The piezoelectric transducer can act both as the source of the vibrations and as the receiver. Several techniques are possible for accomplishing both functions, as described in a later paragraph.

Ultrasonic waves may be thought of as disturbances starting at a vibrating transducer and progressing through a test item, where the transmission of ultrasonic energy depends on particle vibration.

The propagation of ultrasonic waves takes the form of a displacement or disturbance of successive particles (small arbitrary divisions of a material made up of enough molecules so that the material can be thought of as continuous). It should be remembered that the actual particles making up the solid material are not traveling in a direction away from the source but are only vibrating about their mean fixed positions. It is the energy which is moving progressively. If the material is elastic, a restoring force tends to bring each element of the medium back to its original position. Because of inertia, the particles continue to move after they return to the positions from which they started. They reach a position past the original one and then return to the starting position. They then continue to oscillate at continuously diminishing amplitude (distance from original or rest position). Depending on many factors, including the physical characteristics of a given material, the particles execute different movements or orbits as the wave passes through them. The various types of ultrasonic waves are discussed in paragraph 38.

37. APPLICATIONS

Ultrasonics can be applied in an extremely wide variety of ways to nondestructive testing. Each technique usually has advantages and limitations which must be weighed in selecting the optimum test for a given test item.

The most difficult task in ultrasonic testing is selecting the proper technique and apparatus for the particular application and material involved. Also, one of the earliest considerations is the purpose for which the test item will be used. The intended use and function of the material as well as the composition and fabrication methods all have definite bearing on the test selected.

An important consideration that should be kept in mind when testing various items ultrasonically is that if a material is tested early in its processing cycle, the expense of later processing of a defective part may be saved. It should also be remembered that although inspection of a material at one stage of processing may reveal no flaws, inspection at a later stage of processing may indicate: (1) flaws that were not detectable at an earlier stage; or (2) flaws introduced by later processing.

38. WAVE TRAVEL MODES

a. General. All materials are made up of atoms (or tiny particles) lined up in straight lines to form lattices. If the side of this lattice is depressed, the first column of atoms strikes the second column, which in turn strikes the third column, and so on, in sequence. This motion produces a wave movement. The particle movement in the same direction as the wave movement is called the longitudinal, or compression, wave mode.

The illustration in Figure 33 shows two transducers generating ultrasonic waves in the same test item. The transducer on the left is producing longitudinal waves and the transducer on the right is producing shear waves (the particle movement direction is at right angles to the wave movement direction). The velocity of shear waves is approximately half that of the longitudinal waves. The shear wave transducer is mounted on a plastic wedge so that the ultrasonic waves enter the material at a specific angle to produce shear waves.

Shear waves confined to a thin layer of particles on the free boundary (surface and near surface) of a solid are a special type called surface or Rayleigh waves. They propagate with a velocity about 2 percent less than ordinary shear waves. In Figure 34, a transducer mounted on a plastic wedge strikes the test surface at an angle resulting in a surface mode of sound travel in the test item. As shown, a surface wave can travel around a curve, reflecting only at a sharp corner.

Lamb waves (possible only in thin plates) are another type of wave. There are two general classes of waves produced in Lamb wave testing. These are termed symmetrical and asymmetrical waves. An extremely large number of

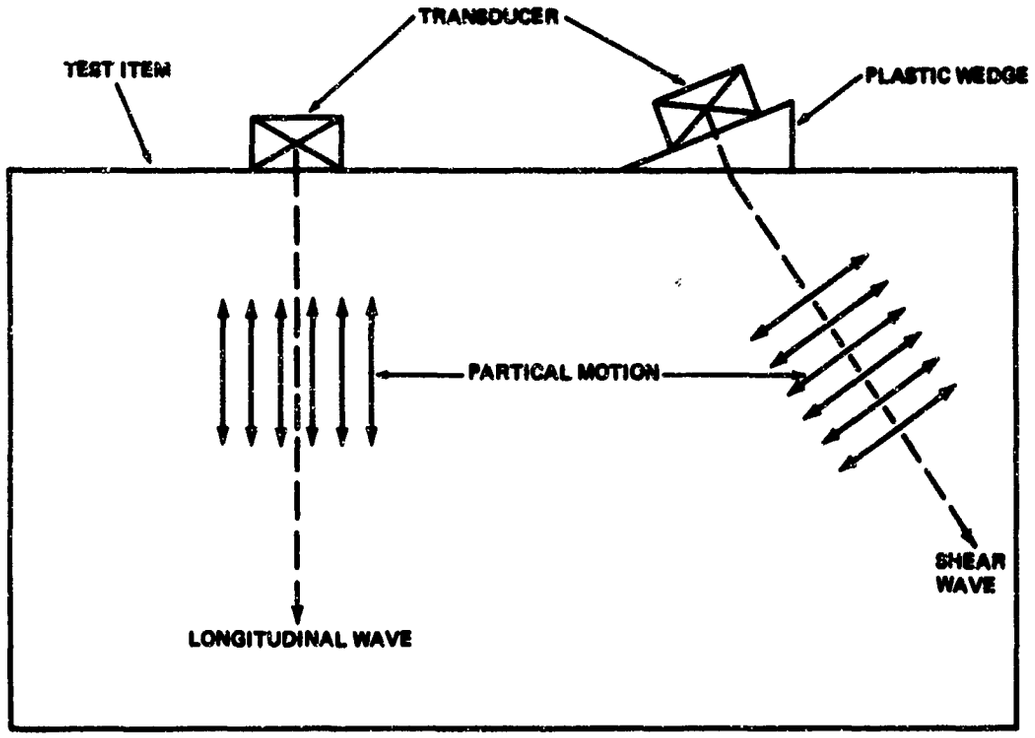


Figure 33. Longitudinal and Shear Wave Modes Compared

Lamb wave modes are possible in a given plate. Each mode propagates with a phase velocity that depends on plate thickness and frequency.

The ability of Lamb waves to flow in thin plates makes them applicable to a wide variety of problems requiring the detection of subsurface flaws. Examples of practical problems for which Lamb waves are used include: (1) immersion inspection of thin-walled tubing and plates for internal defects or grain size determinations; and (2) the testing of welds in butt-welded plates and tubes.

Incident transducer angles can be calculated to produce the types of waves desired for a particular type of testing using anglebeam transducers and making use of Snell's law (after Willebrord Snell or Snellius, c. 1621, a Dutch mathematician). For use in ultrasonics, Snell's law has been modified slightly from its original application which was meant to explain optical refraction. Use of Snell's law in ultrasonics is thoroughly described in the literature and will not be discussed further here.

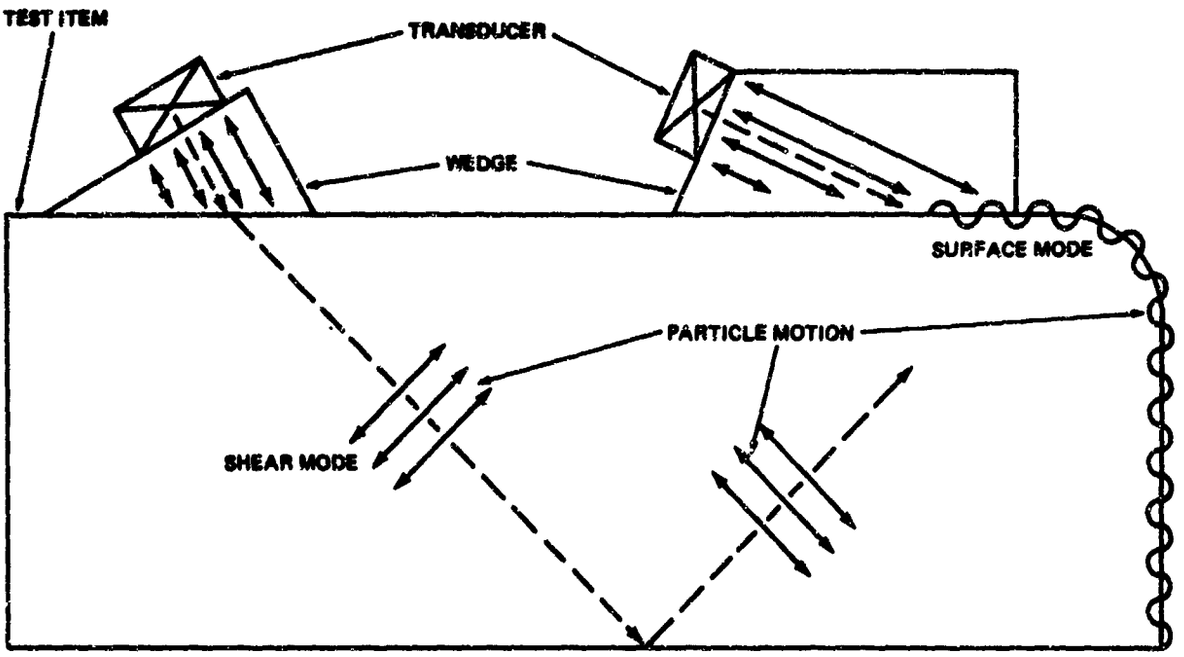


Figure 34. Transmission of Various Ultrasonic Wave Modes

b. Piezoelectric Materials in Wave Generation. An important element in ultrasonics is the phenomenon of piezoelectricity. In general practice, a high-frequency transmitter applies electrical pulses to a "piezoelectric" crystal to generate ultrasonic waves. The prefix "piezo" is derived from a Greek word meaning "to press". Piezoelectricity refers to a reversible phenomenon whereby a crystal, when vibrated, produces an electric current, or conversely, when an electric current is applied to the crystal, the crystal vibrates. This crystal then transforms the electric energy into mechanical vibrations and transmits them through a coupling medium, such as water or oil, into the test material. The three most common piezoelectric materials used in ultrasonic transducers are quartz, lithium sulfate, and polarized ceramics. Common ceramics are barium titanate, lead metaniobate, and lead zirconate.

(1) Quartz. In the past, natural quartz transducers were used almost exclusively, but, with the development of new materials it is being used less and less. Quartz has excellent chemical, electrical, and thermal stability. It is insoluble in most liquids and is very hard and wear-resistant.

Quartz also has good uniformity and resists aging. Unfortunately, it is the least efficient generator of acoustic energy of the commonly used materials. It also suffers from mode conversion interference and requires high voltage to drive it at low frequencies.

When quartz is used for transducers, it is "cut" in either one of two planes. X-cut crystals are cut perpendicular to the X-axis and produce longitudinal sound waves. The Y-cut crystals are cut perpendicular to the Y-axis and produce shear sound waves.

(2) Ceramic. The polarized ceramic transducers are the most efficient generators of ultrasonic energy; they operate well on low voltage, are practically unaffected by moisture, and are generally usable up to about 300° C. They are limited by relatively low mechanical strength, some mode conversion interference, and have a tendency to age (lose their transmission efficiency).

(3) Lithium Sulfate. Lithium sulfate transducers are efficient receivers, and are intermediate as generators of ultrasonic energy. They do not age and are affected very little by mode conversion interference. Lithium sulfate is very fragile, soluble in water, and limited to use at temperatures below 165° F. Lead zirconate is an efficient transducer with good aging characteristics and is often used in modern equipment.

c. Transducer Types. Transducers are made in an extremely wide variety of sizes and shapes from extremely small to wide paint-brush-types; practically any size desired can be made for the laboratory. The many shapes are the result of empirical experience and the requirement for many special applications. The size of a transducer is a contributing factor to its performance. For instance, the larger the transducer, the straighter the soundbeam (less beam spread) for a given frequency. The narrower beams of the small high-frequency transducers have greater ability for detecting very small flaws. The larger transducers transmit more sound energy into the test part, so are used to gain deeper penetration.

(1) Paint-Brush Transducers. The wide paint-brush transducers are often made up of a mosaic pattern of smaller crystals, carefully matched so that the intensity of the beam pattern varies very little over the entire length of the transducer. This is necessary to maintain uniform sensitivity. Paint-brush transducers provide a long, narrow rectangular beam (in cross-section) for scanning. (See Figure 35.)

(2) Double Transducers. The double transducer differs from the single transducer in that the double unit is in essence two single transducers mounted in the same holder. In the double unit, one transducer can be the transmitter and the other the receiver. They may be mounted side by side for straight-beam testing, and stacked or paired for angle-beam testing. In all cases, the crystals are separated by a sound barrier to block cross interference. (See Figure 36.)

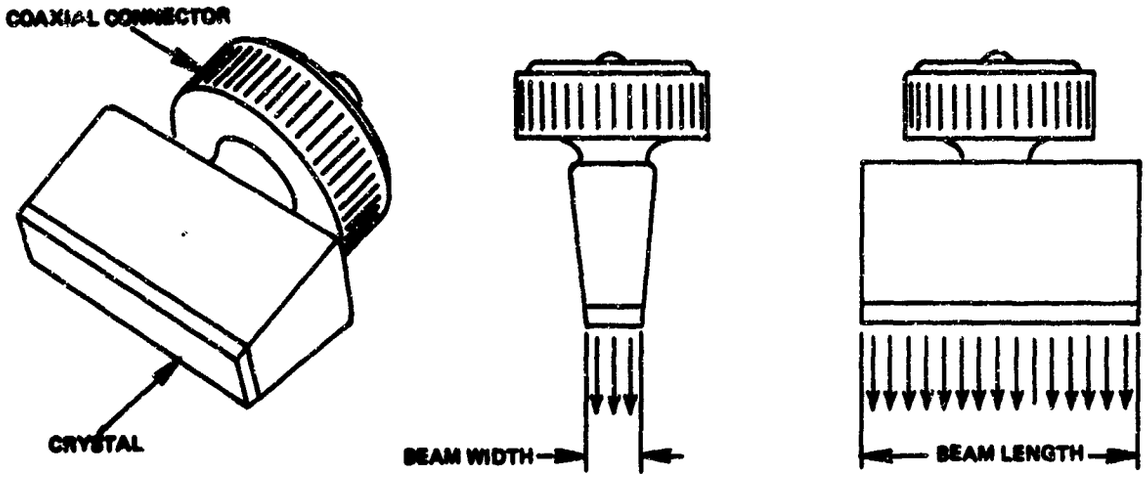


Figure 35. Typical Paint Brush-Transducer

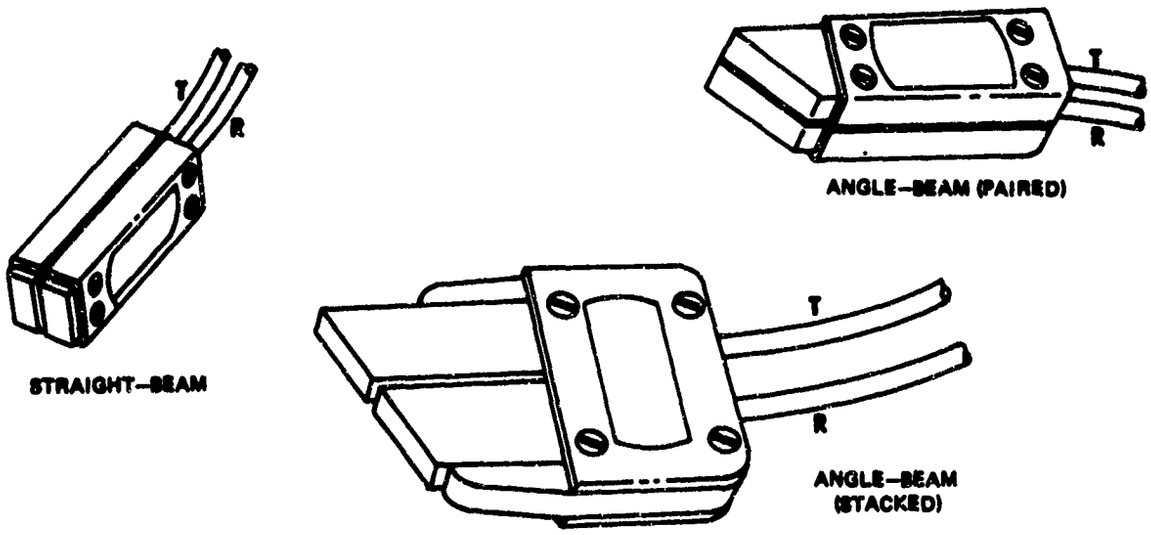


Figure 36. Typical Double Transducers

(3) Angle-Beam Transducers. Transducers are also classified as either straight-beam transducers or angle-beam transducers. (See Figure 37.) The term straight-beam means that the sound energy from the transducer is transmitted into the test item, normal (perpendicular) to the item surface. Angle-beam transducers direct the soundbeam into the test item surface at an angle other than 90 degrees. Angle-beam transducers are used to locate flaws oriented at right angles to the surface and to determine the size of flaws oriented at an angle between 90 and 180 degrees to the surface. Angled transducers are also used to propagate shear, surface, and plate (Lamb) waves into the test item by mode conversion. In contact testing, angle-beam transducers use a wedge, usually of plastic, between the transducer face and the surface of the test item, to direct the sound energy into the test surface at the desired angle. In immersion testing, angulation of the soundbeam is accomplished by varying the angle of a straight-beam transducer to direct the soundbeam through a water path into the test part at the desired angle.

(4) Face Units and Focused Transducers. On contact transducers, wear plates (face units) are often added to protect the fragile crystal from wear, breakage, or the harmful effects of foreign substances or liquids, and to protect the front electrode. Face units can be curved for testing curved surfaces or for focusing the waves.

(5) Resonance Transformers. Transducers with crystals made of quartz, ceramic, and barium titanate are generally used for ultrasonic resonance testing. Many types of transducers are available in a variety of shapes and sizes for specific test applications. (See Figure 38.) The resonant frequency of the transducer is an approximate match to the oscillator selected.

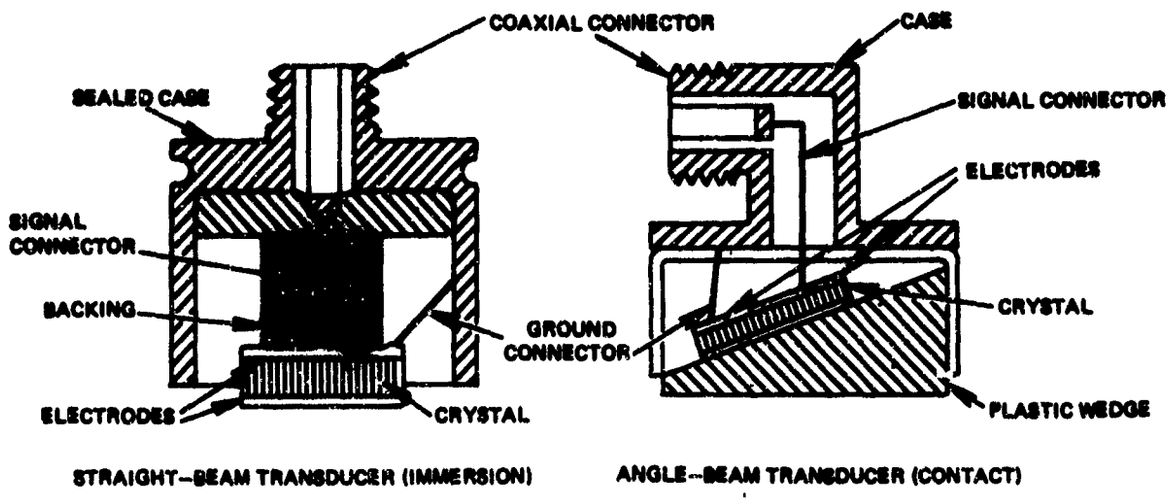


Figure 37. Straight-Beam and Angle-Beam Transducers

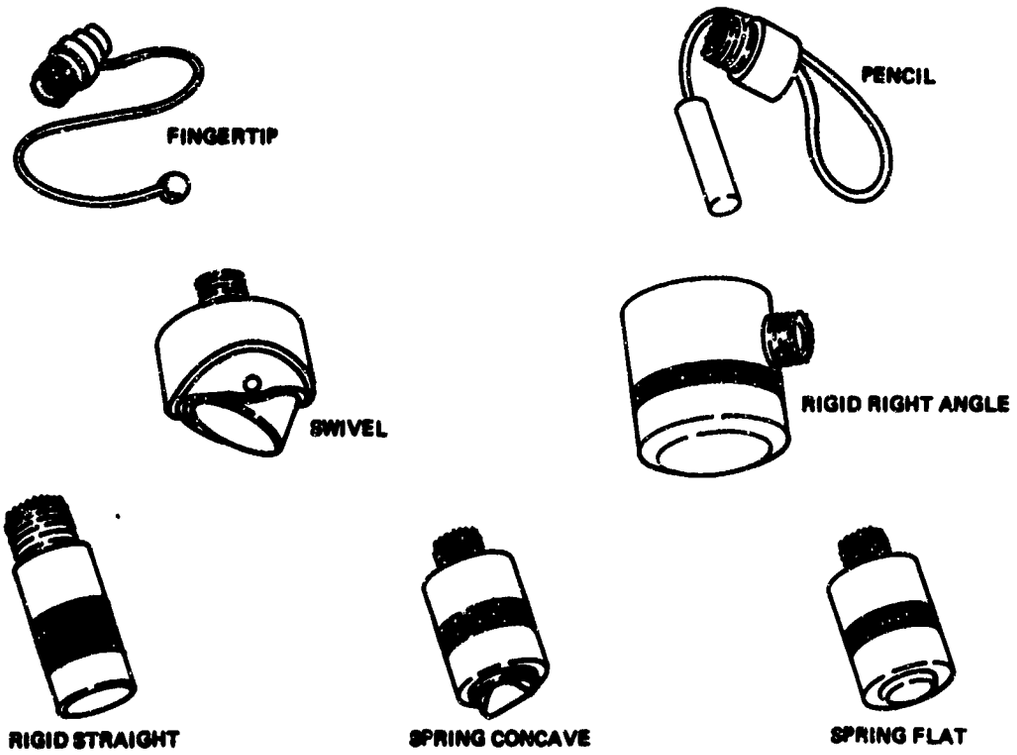


Figure 38. Resonance Transducers

39. SOUNDBEAM TRAVEL

Although an ultrasonic soundbeam is sometimes considered as a straight-sided projection from the face of the transducer, in reality there is always some spreading.

At any frequency, the larger the crystal, the straighter the beam; the smaller the crystal, the greater the beam spread. Also, there is less beam spread for the same diameter of crystal at higher frequencies than at lower frequencies. The diameter of the transducer is often limited by the size of the available contact surface. A large-diameter transducer is usually selected for testing through greater depths of material. The exact amount of spreading for a given size of transducer can be calculated and is described in the literature. In the zone close to the ultrasonic transducer, interference effects are set up in contact testing that confuse signals from this zone (termed the near or Fresnel zone). Various means are used to overcome these near-zone effects, such as standoffs, which are blocks of material designed to be placed between the transducer and the item so that the near-zone effects occur in the standoff material. The "far" zone (also known as the Fraunhoffer zone) in ultrasonic testing is where the effective testing can take place and is that area beyond the area experiencing near zone interference effects and turbulence.

40. ULTRASONIC CONTACT AND IMMERSION TECHNIQUES

a. General. Techniques of ultrasonic testing can be accomplished with contact or immersion testing. In contact testing, the transducer is used in direct contact with the test item, with only a thin liquid film (light oil, etc.) for a couplant. The transducer is moved manually over the surface of the test item. An oscilloscope is used to display the results. The initial pulse pip and the front surface pip on the oscilloscope are usually superimposed or very close together in contact testing. In immersion testing, a waterproof transducer is usually set up under water at a distance from the test item, which is also under water. The ultrasound is transmitted into the material through a water path. The water distance appears on the oscilloscope display as a fairly wide space between the initial pip and the front surface reflection because of the reduced velocity of sound in water.

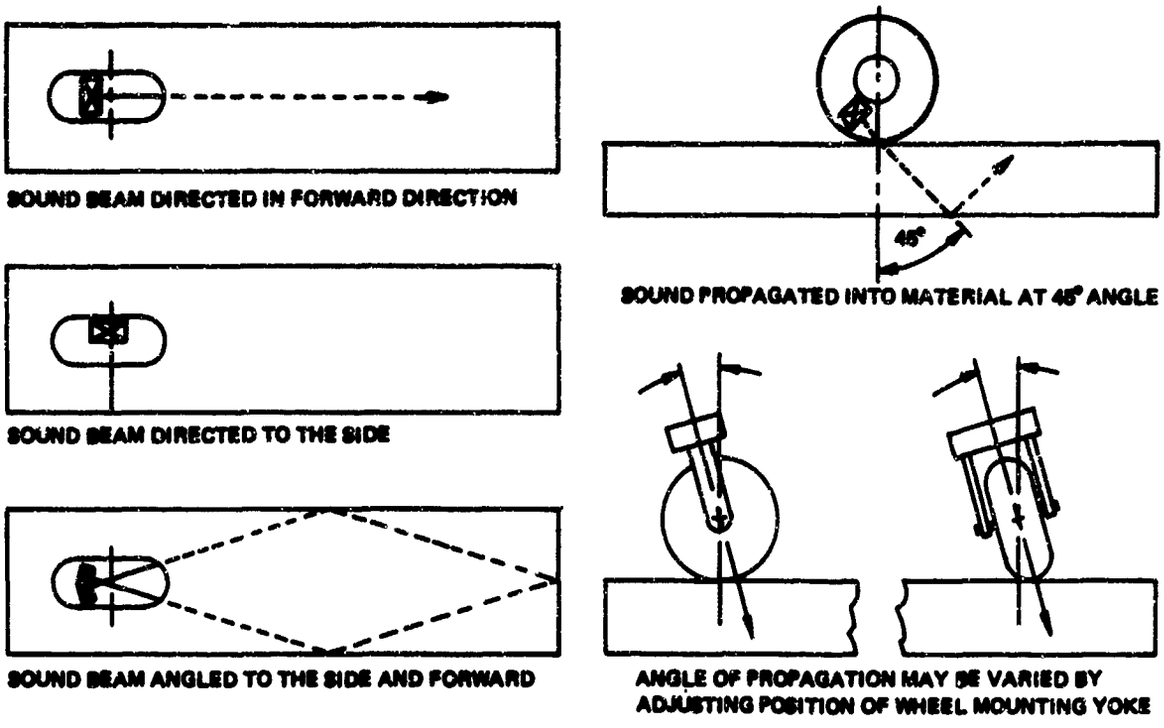
Several variations of immersion testing are possible: (1) immersed technique (where both the transducer and the test item are immersed in water); (2) bubbler or squirter technique (where the soundbeam is transmitted through a column of flowing water); and (3) wheel-transducer technique, where the liquid-filled, tire-equipped transducer rolls on the test surface. (See Figure 39.) In all three of these, further refinements and adaptations are possible, including use of focused transducers.

Contact testing variations include the following: (1) straight beam testing using longitudinal waves; and (2) angle-beam testing using shear waves, surface waves or Lamb waves. Transducers used in contact testing are held in direct contact with the material using a thin, liquid film for a couplant. The couplant selected is high enough in viscosity to remain on the test surface during the test. An even pressure must be maintained on the transducer as it is moved over the item surface.

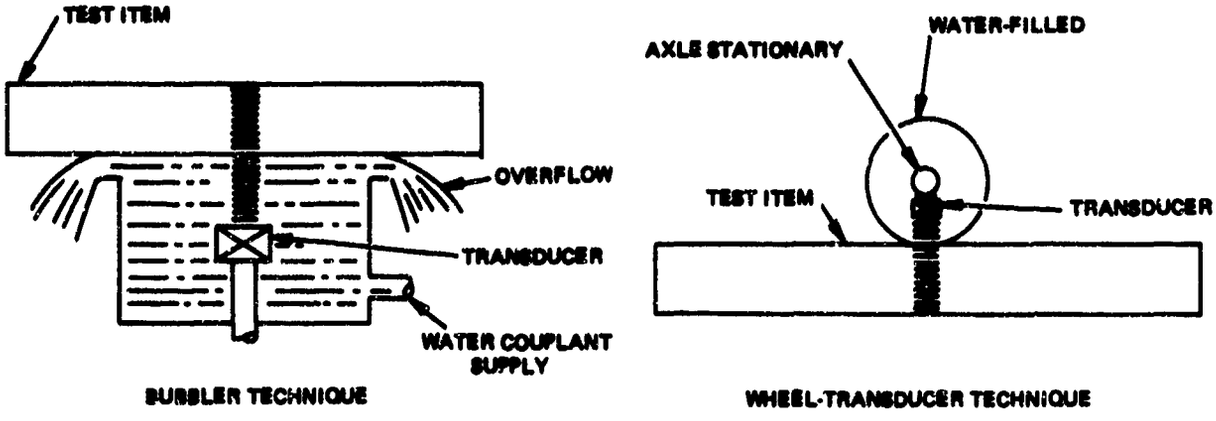
b. Couplants. If a transducer is placed in contact with the surface of a dry part, very little energy is transmitted through the interface into the material because of the great difference in acoustic impedance at the interface. A couplant is, therefore, interposed between the transducer and the test item. Couplants which have been used include transformer oil, SAE 20 motor oil, water, glycerin, benzene, antifreeze, soap-suds, sugar solutions, mercury, and various amalgams. For contact testing, a thin transformer oil is often used. For immersion testing, water works well. Usually, wetting agents are added to the oil or water to insure the elimination of air bubbles which can adversely affect the transmission results.

41. GEOMETRY EFFECTS

a. Shape of Test Item. Part geometry is important in ultrasonic testing. Shapes that contain a number of angles and surfaces sometimes cannot be tested. Grooves, undercuts, and rough surfaces can hide other areas of the test item and can produce indications on the oscilloscope screen that mask the indications caused by internal flaws. Thin sections can often be examined only with certain wave types. Protrusions from test items are often



WHEEL TRANSDUCER ANGULAR CAPABILITIES



BUBBLER AND WHEEL-TRANSDUCER TECHNIQUES

Figure 39. Angle, Bubbler, and Wheel Transducers

difficult to test without contoured transducers. A number of special transducer arrangements and techniques involving introducing the ultrasonic energy from various angles are available for difficult testing problems. Sometimes, experimentation is required to develop the best technique for a particular application.

b. Defect Type Identification. The selection and effectiveness of ultrasonic tests are often determined by the types of flaws expected and the amount of information known about them. If the approximate size, location, and orientation of defects can be predicted accurately, adequate tests are usually easy to set up. When these flaw factors are unknown, it is difficult to set up a totally reliable test. Flaws with rough contours or those extremely thin relative to wavelength are easy to miss. In groupings of these flaws, however, each of the defects scatters some of the incident sound and therefore the group can sometimes be detected by the reduced back reflection in their areas.

42. PULSE-ECHO, THROUGH TRANSMISSION, AND RESONANCE TECHNIQUES

a. General. The nondestructive testing of materials using ultrasonic testing can be divided into the following basic test techniques.

(1) Pulse-echo.
(2) Through transmission.
(3) Resonance.

b. Applications. Of the three basic test techniques, pulse-echo and resonance are most often used in the fields of thickness measurement and flaw detection.

Pulse-echo techniques offer significant advantages over the others, particularly in applications where: only one surface of the test item is accessible; large volumes of material must be inspected for internal flaws; or results must be immediately available (as in production line testing).

c. Pulse-Echo Techniques.

(1) General. World War II provided pulse-echo circuitry for radar. Since then, ultrasonic testing instrumentation has developed using this principle. Ultrasonic pulse-echo testing has become a more widely used and accepted method. Instruments are now available which can be effectively operated by persons with limited training. A typical pulse-echo system is shown in the upper portion of Figure 40.

Pulse-echo testing can be performed by either the two search unit or the single search unit reflection technique. The two unit technique is used when the test material is of irregular shape and reflecting surfaces (or the back surface) are not parallel with the entrant surface.

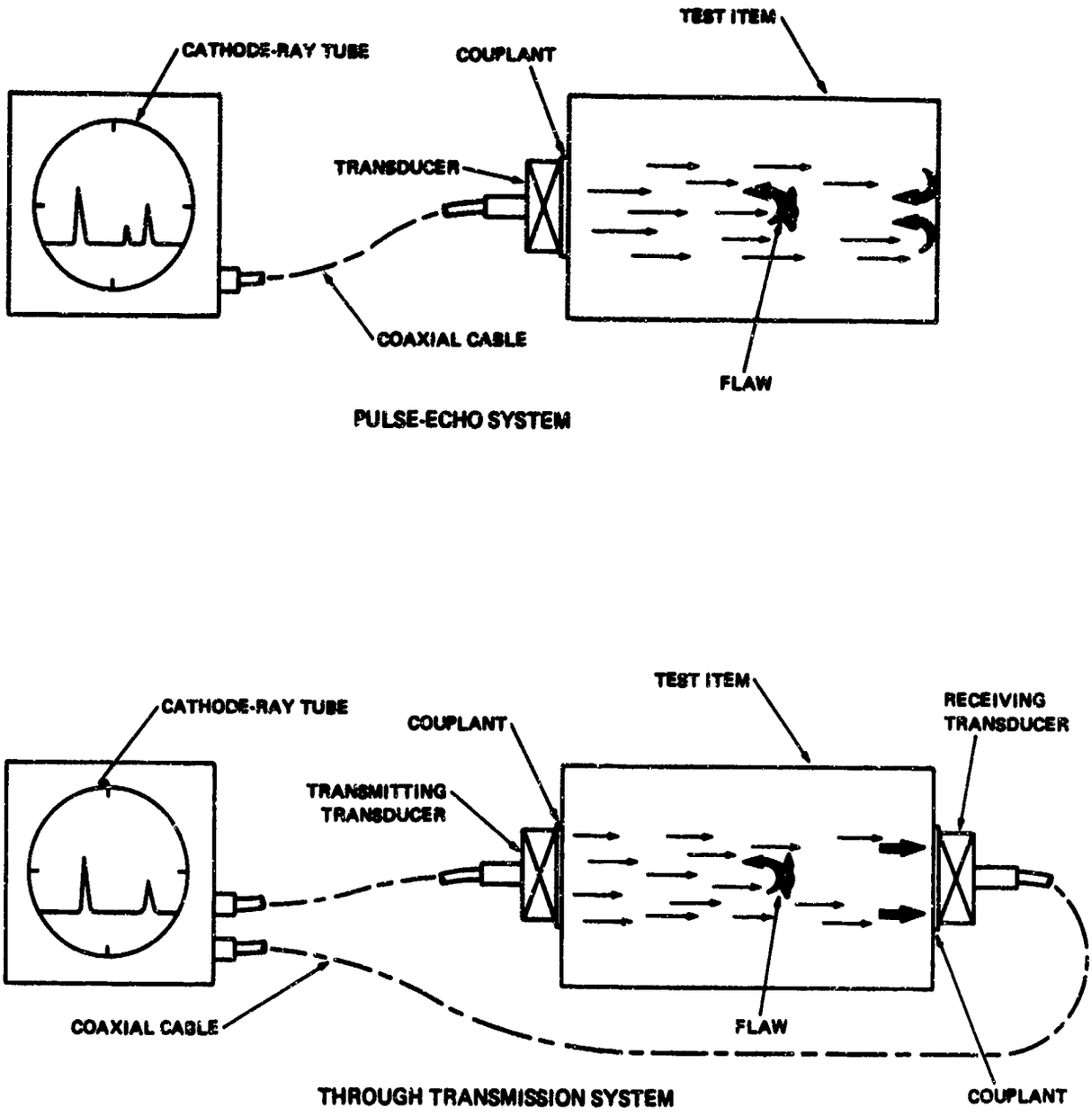


Figure 40. Pulse Echo and Through Transmission with A-Scan Presentations

(2) The Two Unit Pulse-Echo Technique. This method involves using one search unit as the transmitter and the other as the receiver. The transmitter sends a pulsed beam of energy into the test item. The waves travel through the material and are reflected back to the receiving unit from any flaws or from the opposite boundary if it is parallel to the entrant surface.

(4) A-Scan. When pulse-echo vibrational energy returns to the transducer it is transformed into electrical energy, amplified, and presented as a vertical pip on a cathode ray tube (CRT) or oscilloscope. This type of presentation is known as an A-scan. This method does not give direct information about the exact nature of the reflections. The desired information is obtained by correlating information from several sources. The first consideration is the nature of the test material and its construction. An A-scan was shown in Figure 40.

Since the front surface echo and the echo from the flaw are received before the echo from the back surface of the test item, the time relationships can be correlated to obtain the distance of the flaw from the transducer and from the back surface. The initial pulse (or main bang) and the echo from the back surface produce two sharp rises or "pips" from the horizontal trace or baseline on the oscilloscope.

The initial pulse is indicated on the left side of the screen followed by the pip from the flaw and then the pip from the back surface.

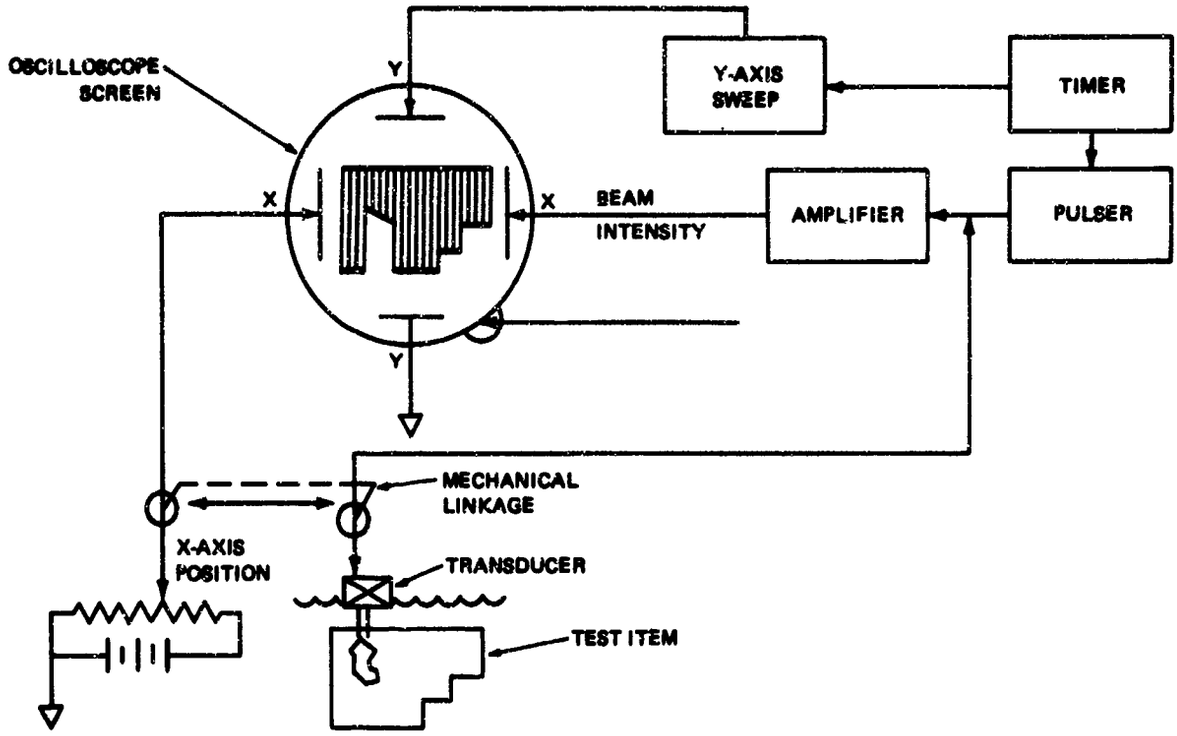
(5) B-Scan. The B-scan presentation is used for medical applications as well as in nondestructive testing. (See Figure 41 for illustrations of B- and C-scans.) The B-scan provides a cross-sectional view.

(6) C-Scan. The C-scan provides a plan view or the shape of a flaw as viewed from the front surface. The view is similar to that provided by an X-ray picture. A contour of a flaw can thus be obtained. The front and back surfaces are not visualized with the C-scan type of presentation. Only the reflection from the flaw is shown.

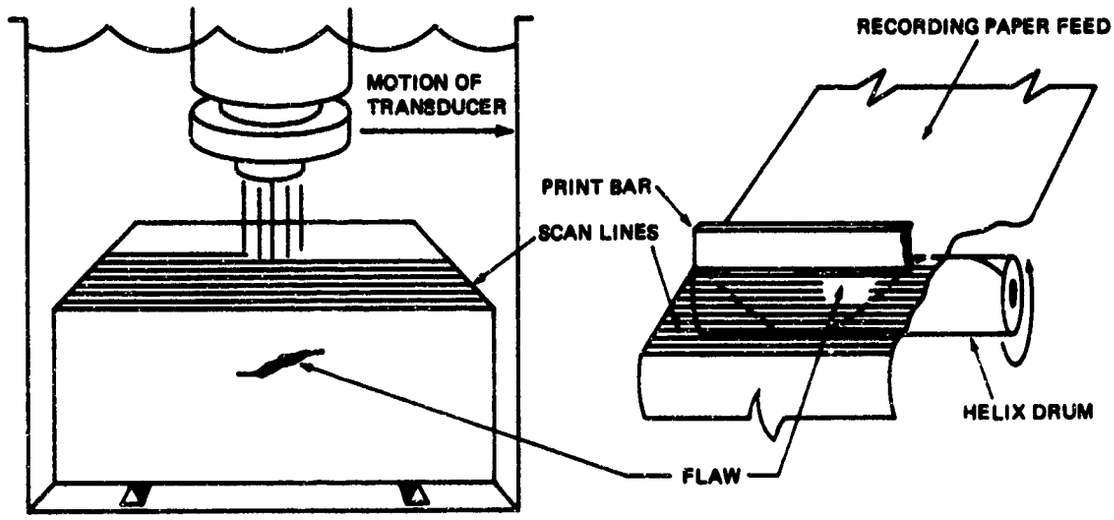
d. Through Transmission. Two search units are placed at opposite sides of a test item in this method. One transmits energy straight through the test item and the other picks up the transmitted energy. Any flaws in the path of the beam will cause a reduction in the amount of energy reaching the receiving search unit.

As in pulse-echo transmission, short pulses of energy are transmitted into the test item (or continuous waves can be used if desired). Unlike the pulse-echo system, the energy does not return to the transmitting transducer. The through transmission system indicates flaws in a test item by variations in received energy amplitude. (Refer back to Figure 40.)

e. Resonance Testing. The resonance system uses energy transmitted into a test item in a manner similar to that of the pulse-echo system, except that the waves used are always the continuous, longitudinal type.



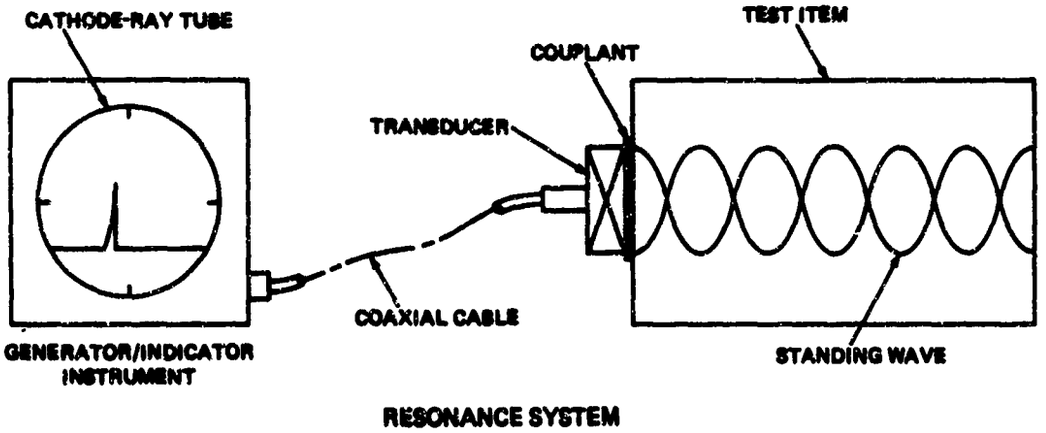
B-SCAN PRESENTATION



C-SCAN PRINCIPLE OF OPERATION

Figure 41. Ultrasonic Testing B- and C-Scans

Wave frequency is varied until standing waves are established in the test item, causing the item to resonate or vibrate at a greater amplitude. Resonance is then sensed on the generator/indicator instrument and presented as a pip on the CRT screen, a meter deflection, or an audible sound change detected by means of an earphone. A change in resonant frequency which cannot be attributed to change in material thickness is usually an indication of a flaw. (See Figure 42.)



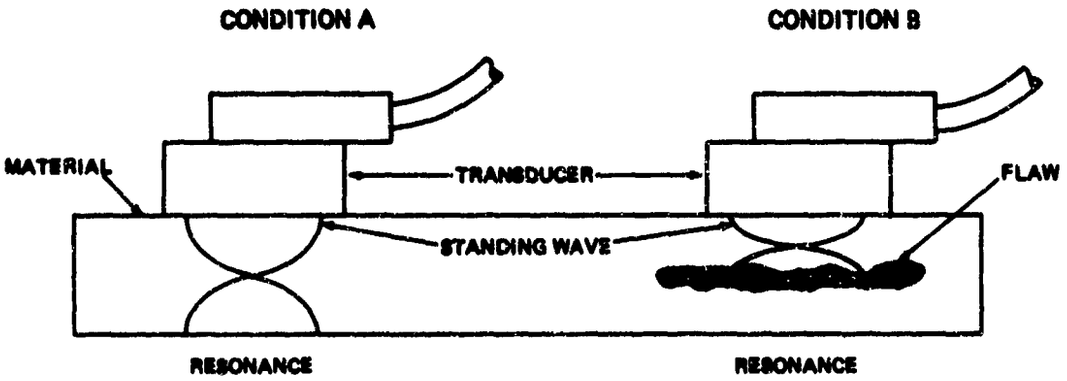


Figure 42. Ultrasonic Resonance Testing

43. IMAGING TECHNIQUES AND SYSTEMS

The possibility of using television-type scanning techniques to produce a high-speed display of an ultrasonic field was proposed by S. Sokoloff in the 1930's. Instruments are now commercially available which operate on this principle. The general concept of operation is based on the idea that if an extended area of piezoelectric material is subjected to ultrasonic energy at some point on its surface, a potential is produced at that point rather than over the entire surface of the material. If this surface is scanned by a high velocity electron beam, it generates signals which (after amplification) are displayed as intensity modifications on the picture tube of a closed circuit TV system. Hence, ultrasonic energy passing through an object produces varying potentials on the piezoelectric target. These varying potentials are characteristic of the flaws in the object. The electron beam scans the target and is modulated by the varying potential on its surface. The modulated beam is then carried to the television screen. What finally appears is a visual representation of the flaws.

Ultrasonic television techniques have been applied to flaw detection, weld inspection, and inspection for unbonded areas. The television scanning method of testing is not widely used at present and is still considered by many to be in the developmental stage. The technique holds promise for future use, however, since visual indications and exact shapes of flaws can be determined.

A number of techniques have been used to make ultrasonic presentations similar to X-ray pictures. These are described in the literature and are not presently of wide significance in general testing.

A means of preserving an image on an oscilloscope often becomes useful in ultrasonic testing to record a particular presentation. Oscilloscopes equipped with special cameras are widely available and many variations exist for special purpose photographing of oscilloscope presentations.

44. ATTENUATION

In solids, attenuation or dissipation of energy results as the ultrasonic wave travels through the material and its energy is reduced by scattering, absorption, and beaming.

Scattering is caused by a partial refraction of the beam at each of the many small grain-boundary interfaces. With fine-grain structure, the losses are not significant. Where the material particles are segregated along grain boundaries, however, much energy may be scattered, resulting in poor ultrasonic penetration.

Absorption results from the low elasticity of a material. The ability of a material to transmit ultrasonic vibrations is partially dependent on the elasticity of the material. The measure of elasticity is the elastic modulus, which is the ratio of stress or force on a particle to the strain or elastic deformation. Materials with a low modulus of elasticity tend to absorb more sound.

Attenuation also results from divergence or beaming phenomena. In ultrasonics, beam divergence increases as the frequency is reduced or as the dimensions of the search unit crystal are reduced.

Frequency affects attenuation in the following manner. Attenuation losses generally increase rapidly with increases in frequency. This principle may be used in selecting the optimum frequencies and transducers for use in a particular test. Distance-amplitude correction curves can be made for correction of attenuation in test items. The technique for calculating such curves is described in the literature.

Attenuation corrections may be made electronically in test equipment so that the amplitude of display signals on CRT's will be nearly equal for reflectors of equal size but of different distances from the vibrating crystal. Each instrument manufacturer usually has his own name for such attenuation controls, e.g., time corrected gain (TCG), distance amplitude correction (DAC), swept gain, and so forth.

45. INTERPRETATION OF ULTRASONIC TEST RESULTS

a. General. Some of the foremost problems encountered in ultrasonic testing are: (1) providing an adequate and standardized indication of where ultrasonic testing should be performed and (2) obtaining standardized methods and references. Results should be correlated with destructive test results when this is possible.

It is also desirable to provide the test operator with enough guidance to allow him to determine permissible deviations from the normal and flaws which are undesirable for various applications. Applicable standards and specifications are available from such agencies as ASTM, ASA, ASNT, and the Government.

A general procedure for ultrasonic testing is provided as follows:

(1) The test item should be divided into areas suggested by its natural boundaries and a table provided of the type of scan to be applied to each area.

(2) For each scan, it should be stated whether or not a boundary echo will be obtained and, also, if other indications will be present, e.g., from shoulders, holes, mode conversion, etc.

(3) The areas, if any, that will require surface preparation should be indicated.

(4) The reference test blocks to be used and the sensitivity to which the flaw detector should be set should be noted. This may require a stipulation for defects nearer the surface as they may appear disproportionately large if sensitivity has been set for a distant target.

b. Reference Standards. Ultrasonic test indications from subsurface flaws within the test item are usually related or compared to those from standard test blocks having flat-bottomed holes of varying depths or diameters. These comparisons are fairly accurate for evaluating the approximate size, shape, position, orientation, and impedance of flaws. Test conditions and the flaws themselves sometimes cause ultrasonic phenomena which are difficult to interpret. This difficulty may be resolved by experience in relating the ultrasonic indications to the probable type of flaw with reference to the test conditions. Impedance of the material, surface roughness, surface contour, attenuation, and angle of incidence are all considered when interpreting the size and location of an unknown flaw. The simplest method is to compare the flaw with a test block similar to the test item. The experienced operator also learns to discriminate between the indications from actual flaws and those of no interest (false or irrelevant indications).

c. Typical Immersion Test Indications.

(1) General. Immersion test indications, often displayed on A-scan pulse-echo units, are generally interpreted by analysis of three factors: amplitude of reflection from a flaw, loss of back reflection, and distance of flaw from the surfaces of the test item. Individual flaws that are small (compared with the transducer crystal diameter) are usually interpreted by comparing the amplitudes of the test item echoes with the echoes from flaws in reference test-blocks. The surface of the test item and the surface of a flaw within it are generally not as uniform as the surface of the test block and the flat-bottom hole in the test block. Therefore, flaws in the test item may appear a bit smaller than the actual size when compared to test block flaws.

(2) Irrelevant Indications. Reflections from fillets and concave surfaces in a test item may result in responses displayed between the front and back surfaces and may be mistaken for reflections from flaws. Broad-based pips (as contrasted to a sharp spike or pip) are likely to be reflections from a contoured surface. Near the edges of rectangular shapes, edge reflections are sometimes observed. This type of indication usually occurs when the transducer is within 1/2 inch of the edge of the test item.

Articles with smooth, shiny surfaces will sometimes give false indications. For example, a thick aluminum plate machined to a smooth finish may give spurious indications which appear to be reflections from a flaw located about 1/3 of the article depth. As the transducer is moved over the surface of the plate, the indication remains relatively uniform in shape and magnitude. Apparently this type of indication results from surface waves generated on the extremely smooth surface, possibly reflecting from a nearby edge. They may sometimes be eliminated by coating the surface with wax crayon or a very thin film of petroleum jelly.

(3) Angled-Plane Flaw Indications. Flaws oriented with their principal plane at an angle to the front surface are sometimes difficult to detect and interpret. Usually, it is best to scan initially at a comparatively high

gain setting (high sensitivity), to detect such angled-plane flaws. The transducer is then manipulated around the area of the flaw to estimate its magnitude. Bursts in large forgings fit this category, and tend to lie at an angle of 45 degrees to the surface.

(4) Grain Size Indications. Unusually large grain size in the test item may produce "hash" or noise indications. In some cases, abnormally large grain-size results in a total loss of back reflection. These large grain conditions are generally a result of prolonged or improper processing temperatures. Grain size affects the attenuation characteristics of the test item.

d. Typical Contact Test Indications.

(1) General. Contact test indications, in many instances, are similar or identical to those discussed in the previous paragraph on immersion test indications. In contact testing, interference from the initial pulse at the front surface of the test item and variations in efficiency of coupling sometimes produce irrelevant effects that are sometimes difficult to recognize. As in immersion testing, signal amplitude, loss of back reflection, and distance of the flaw from the surfaces of the article are all major factors used in evaluation of the display.

(2) Dead-Zone Indications. The dead zone is the length of the soundbeam path, after entering the test material, during which no reflections are displayed because of obstruction by the initial pulse. In immersion testing, the initial pulse is separated from the front-surface pip by the water path. In contact testing, a standoff (such as a plastic block) is placed between the transducer and test item to eliminate dead zone effects in the test item. In most contact testing when a single transducer is used to transmit and receive, the initial pulse obscures the front surface indications. With straight-beam transducers, near-surface flaws may be difficult to detect because of this initial-pulse interference. Shortening the initial pulse may allow detection of near-surface flaws that are obscured by the ringing "tail" of a long initial pulse. (See Figure 43.) Also, pitch and catch transducers can be used to reduce dead zone effects, since one transducer is used to transmit and the other to receive. With pitch-and-catch testing, using two transducers, the initial or transmitted pulse does not interfere with reception, as with the single transducer.

(3) A-Scan Indications for Typical Flaws. In Figure 44, oscilloscope displays are shown for various typical flaws (shown directly below the oscilloscope presentation) detected during contact ultrasonic testing.

(4) Irrelevant Indications. Coarse-grain material causes reflections or "hash" across the width of the display when the test is attempted at a high frequency. To reduce the effect of these unwanted reflections, the frequency is lowered and the direction of the soundbeam changed by using an angle-beam transducer. When testing cylindrical items (especially when the face of the transducer is not curved to fit the test surface) irrelevant pips appear following the back surface echo.

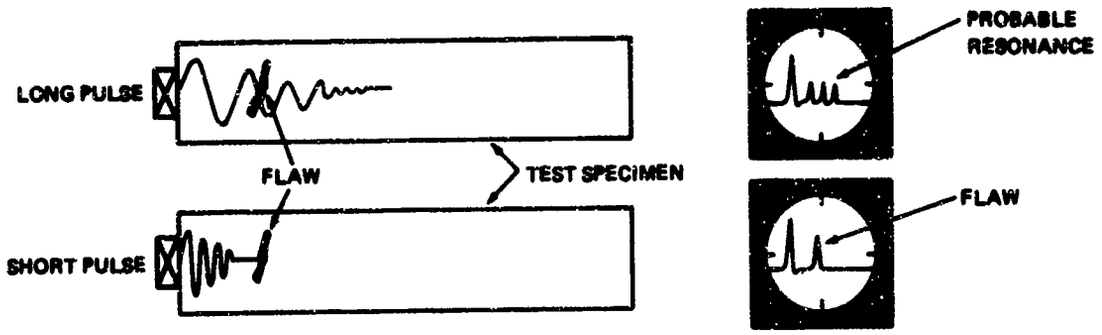
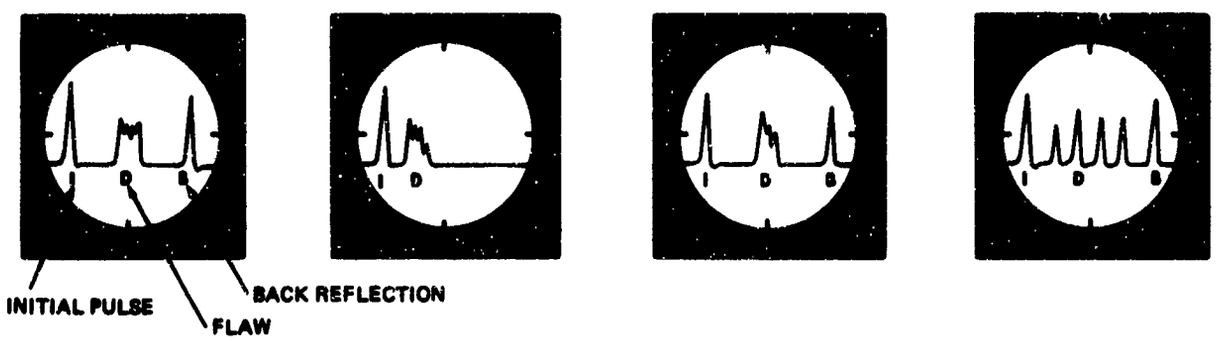


Figure 43. Long and Short Pulse Effects on Display

NOT REPRODUCIBLE



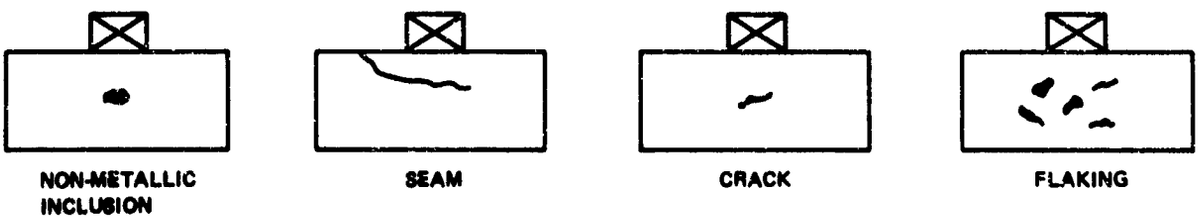


Figure 44. Typical Contact Test Flaw Indications

In testing long items with straight beam testing, mode conversion sometimes occurs from the soundbeam striking the sides of the test item and returning as reflected shear waves. This problem can sometimes be overcome by changing to a larger transducer. Surface waves generated during straight beam testing can also cause unwanted irrelevant indications when they reflect from the edge of the test item. Many other types of irrelevant indications are possible and can be recognized only after experience with the various types of testing and apparatus.

e. Summary. As in most physical testing, ultrasonic inspection involves three basic steps: instrument calibration, test item inspection, and interpretation of data obtained from the inspection. To be of maximum value, these operations must be performed in some predetermined manner and standard sensitivity levels used. The required framework is the specification to which the test is performed.

The final results will be no better than this framework, i.e., the extent to which the specification clearly defines the test objectives, procedures, and acceptance levels. The test system must also be properly calibrated.

To be widely applicable, the optimum calibration technique should calibrate the entire system including the instrument used, the search unit, positioner, and indicator or recorder.

A considerable number of specifications and standards for ultrasonic testing now exist in the United States. They range from the relatively general to the very specific.

Some of these are mandatory and others are only suggested guidelines. Almost all stages of material processing, fabrication, and maintenance are covered by various pertinent documents.

46. ULTRASONIC EQUIPMENT

a. A-Scan Equipment. The A-scan system is a data presentation method to display the returned signals from the material under test on the screen of an oscilloscope. The horizontal baseline on the oscilloscope screen indicates elapsed time (from left to right), and the vertical deflection shows signal amplitudes. For a given ultrasonic velocity in the test item, the sweep can be calibrated directly, across the screen, in terms of distance or depth of penetration into the sample. Conversely, when the dimensions of the sample are known, the sweep time may be used to determine ultrasonic velocities. The vertical indications or pips represent the intensities of the reflected soundbeams. These may be used to determine the size of the flaw depth or distance to the flaw from the front or back surface, soundbeam spread, and other factors. Most A-scan units incorporate an oscilloscope screen coated with a medium-persistence phosphor. The chief advantage of this equipment is that it provides amplitude information needed to evaluate the size and position of the flaw. It should be remembered that the indication information is indirect and must be correlated and interpreted to provide information regarding flaw size and depth.

b. B-Scan Equipment. The B-scan equipment, in addition to the basic components of the A-scan unit, provides the following functions:

(1) Retention of the image on the oscilloscope screen by use of a long-persistence phosphor coating.

(2) Deflection of the image-tracing spot on the oscilloscope screen synchronized with motion of the transducer along the sample.

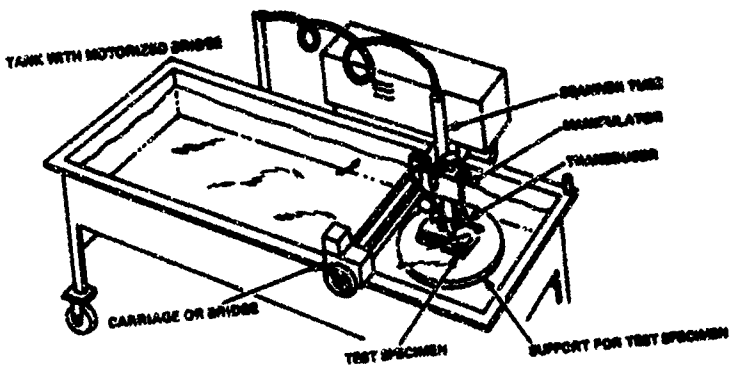
(3) Image-tracing spot intensity modulation or brightening in proportion to the amplitude of the signals received.

The B-scan system is particularly useful where the distribution and shape of large flaws within a sample cross-section are of interest. The sweep connections on the oscilloscope are made to the vertical Y-axis of the cathode ray tube, and the amplifier/position signals are routed to the horizontal X-axis. In high-speed scanning, the cross-section image is retained long enough to evaluate the entire test item and to photograph the oscilloscope screen for a permanent record.

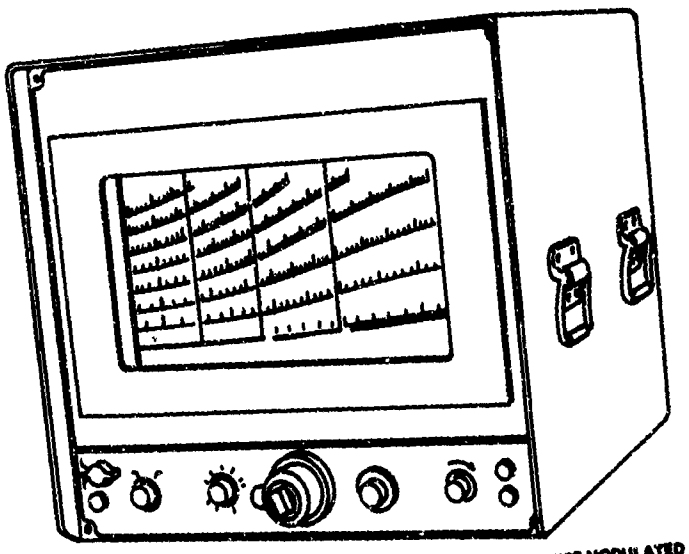
c. C-Scan Equipment. C-scan equipment provides permanent record of the test when high-speed automatic scanning is used. C-scan displays the flaws in a plan view, but provides no depth or orientation information. C-scan recorders often employ a chemically-treated paper that is passed between a printing bar and a helix drum. The printing bar is connected electrically to one of the output terminals of the amplifier in the ultrasonic test unit. The other terminal is connected to the helix mounted on the helix drum. As the drum turns, the sliding contact point between the bar and the helix moves back and forth across the paper. Variations in electric current at the contact point determine the amount of print-out produced on the paper. One revolution of the drum produces one line of scan.

The paper movement is synchronized with the movement of the transducer across the test surface. The amplifier is also connected to the oscilloscope so that, whenever a signal (pip) of predetermined amplitude is displayed, a change of current occurs in the printing bar contact. In this manner, a record of the flaws is produced as the transducer scans the test surface. Some recorders produce a shaded scan line to indicate the outline of the flaw. On others, the flaw outline may be indicated by the absence of the scan lines. The printout of some recorders may be reversed. The extent of the marked (or unmarked) area of the recording indicates the size of the flaw. The same type of signals that generate the pips on the A-scan, produce a change on the C-scan recording. The front and back surface signals from the test item are eliminated from the C-scan recording by gating circuits, and the flaw sensitivity control setting determines the amplitude of the signal (pip) required to produce a change on the recording.

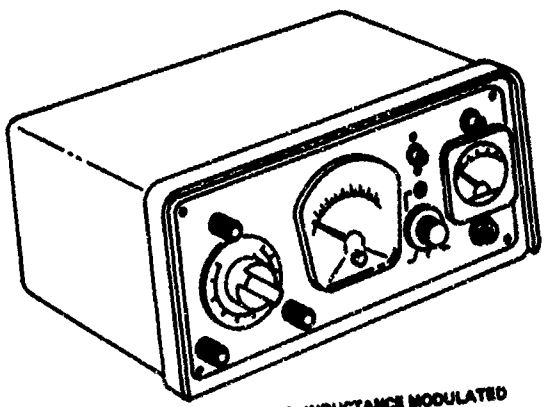
d. Specific Items of Equipment. As indicated by the foregoing discussion, a wide variety of commercial ultrasonic equipment is available. Some of this is illustrated in Figure 45. The equipment includes ultrasonic



TYPICAL IMMERSION SYSTEM



OSCILLOSCOPE-TYPE RESONANCE THICKNESS TESTER, INDUCTANCE MODULATED



METER-TYPE THICKNESS TESTER, INDUCTANCE MODULATED

Figure 45. Resonance Thickness Testers

tanks and bridge/manipulators which are necessary for high-speed scanning of immersed test items. Modern units consist of a bridge and manipulator, mounted over a fairly large water tank, to support a pulse-echo testing unit and a recorder. Drive power units move the bridge along the tank side rails, while transversing power units move the manipulator from side to side along the bridge. Most of these units are automated, although some early units are manually operated.

e. Ultrasonic "Color" Equipment. Color displays for ultrasound cameras have been described in the literature and are the result of work sponsored by the National Television System Committee (NTSC). Displays obtained to date with color systems indicate that it is possible to detect acoustic impedance changes to a high degree of sensitivity. This greatly increased sensitivity promises to expand the uses of the ultrasound camera greatly in nondestructive testing.

47. ADVANTAGES AND DISADVANTAGES

a. Ultrasonic Testing Advantages:

(1) Ultrasonic inspection can be used to detect extremely small flaws.

(2) Ultrasound can be focused to provide high sensitivity in small regions.

(3) Ultrasonic tests can be used to measure the thickness of plates, sheets, coatings, and layers.

(4) Since ultrasound travels great distances in fine-grained materials, it can be used to detect flaws in such materials which are far from the transducer contact area.

(5) Ultrasound is adaptable to the scanning of test objects immersed in a bath.

(6) The attentuation of ultrasound can be related to the grain size, fatigue damage, stress, and structure of the test object.

(7) Many ultrasonic tests can be adapted to automation.

b. Ultrasonic Testing Disadvantages:

(1) A couplant must be used between the transducer and the test object.

(2) The detection of small flaws in objects of large surface area can be tedious and time consuming -- especially if the test object cannot be put in a bath for scanning.

(3) Ultrasound is attenuated by coarse grain materials.

(4) Complexly shaped objects must be manually scanned.

(5) Objects touching the surface of test articles, such as soil around a pipe, can interfere with surface and Lamb waves.

Section VIII. EDDY CURRENT NDT

48. BACKGROUND

Electromagnetic testing is a term which describes the broad spectrum of electronic test methods involving the interaction of magnetic fields and circulating currents. The most widely applied technique within this entire category is eddy current testing. This consists of inducing eddy currents in test items by means of special coils and measuring the resulting fields with suitable measuring and indicating instruments.

The use of electromagnetic waves for nondestructive testing outdates even the experimental proof of the reality of these waves. D. E. Hughes was able to distinguish between different metals and alloys with eddy currents several years before Hertz demonstrated the existence of electromagnetic waves. Hughes published an account of his experiments in the Philosophical Magazine in 1879. Subsequent development work proved that eddy current nondestructive testing was sensitive to almost any type of change within the test object itself. In fact, the extreme sensitivity to a wide variety of materials and conditions proved to be the greatest difficulty in applying the technique in NDT. It was not until after World War II that developments in electronics and electromagnetic wave propagation made it practical to apply eddy current testing techniques to industrial inspection. Since that time, sophisticated instruments have been successfully developed and applied so that it can now provide inexpensive, high-speed nondestructive testing with the accuracy and stability required to meet industrial needs. Such equipment is compatible with industrial requirements and is often integrated into manufacturing processes to provide completely automatic inspection, qualification, and segregation of objects as they are being cast, formed, or machined.

Such testing has often served to speed up inspections which were previously performed visually or manually, and in some cases has offered 100 percent inspection where only sampling and destructive testing were previously possible. For example, tubing can now be inspected through the use of eddy current techniques for defects and flaws at tube speeds up to 6,000 feet per minute. Comparable visual inspection would be less comprehensive, subject to much greater error, and would proceed at a speed of less than one-half of one percent of the automated eddy current method.

The eddy current phenomenon may be described essentially as follows. When a mass of conducting material is moved in a magnetic field or is subjected

to a changing magnetic flux, eddy currents circulate in the mass. These eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux.

In electromagnetic testing and inspection, these principles are implemented by combining a probe, a test sample, and an instrument so that the alternating electromagnetic field produced by the probe creates an eddy current distribution within the test sample. This eddy current distribution produces an alternating electromagnetic field which is proportional to the homogeneity and composition of the test material, and is opposed to the original electromagnetic field.

The eddy current method should be used only where most advantageous and should not be looked upon as a solution to every NDT problem. Those wishing to expand their knowledge of eddy currents and their application will find ample additional information presented in NDT handbooks, journals, and reports.

49. EDDY CURRENT EQUIPMENT REQUIREMENTS

a. General. In eddy current testing, more so than in any other method of NDT, the testing system is designed to fulfill a particular need. The testing parameters which influence the choice of one system over another are just as important as the test system itself. In making a selection of the system to be used first analyze the problem.

The validity of the test depends on the capability of determining which system (equipment) will be required to resolve the specific problem (task).

b. Test System Components. A variety of test probes, frequencies, and instruments are available. Generally, the term test probe refers to an electromagnetic transducer placed on the surface of a test object. The term test coil refers to a transducer which encircles the test object. The test coil is generally a coil of wire with electrical properties compatible with the instruments with which it is used. In addition to this coil of wire, there is often a piece of ferrite material (test probe) which is designed to shape and focus the electromagnetic field. By using such core material, it is possible to direct the electromagnetic field emanating from the coil of wire to the specific area of the test item to be inspected and thereby increase the resolution and sensitivity of the test.

The proper test frequency for a specific eddy current application can be determined approximately by the use of formulas and tables. In general, the test frequency determines the depth of inspection into a test item and the sensitivity to such parameters as the electrical conductivity and magnetic permeability of the test item. As the test frequency is increased, the depth of penetration into the test item decreases and the eddy current distribution becomes denser at test item surface.

Instrumentation is commercially available with a wide range of test frequencies. This frequency range provides a range of depth penetration from

approximately 0.500 inch to less than 0.001 inch. Tests can be performed on items of very large size (tank turrets, engine blocks, etc.) as well as very thin wires and other small parts.

While there are many different test frequencies, probes, and coils provided by manufacturers of eddy current instrumentation, there are basically two types of instruments: dual differential instruments and absolute instruments. (See Figure 46.) The number of test probes associated with an instrument is indicative of its type. For example, a dual differential instrument has two identical test probes that are electrically opposed. Metallurgical or geometrical differences within a test item or between test items are detected and displayed by this type of instrument.

The absolute test instrument has only one test coil or probe associated with it. In this type of instrument, the metallurgical or geometrical differences between test items — or the presence of a defect or flaw — change the properties of the test coil, and thereby produce an indication on the instrument's display system.

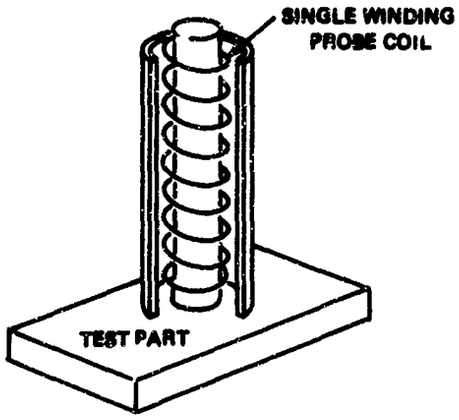
c. Instrumentation Selection. Both instruments just described produce similar information regarding the properties of the test item, but their operating characteristics are quite different. This difference plays a large role in the selection of an eddy current instrument for a given application.

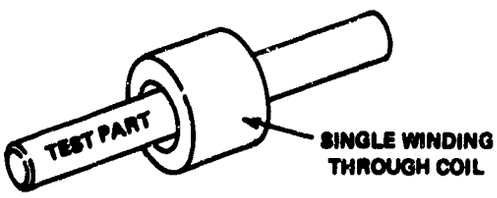
In metallurgical evaluations of a test item for such properties as hardness or alloy measurement, the dual differential type instrument offers an inherent stability which allows a high degree of sensitivity and repeatability. These qualities make this type of instrument ideal in an automated system for high volume and high-speed inspections. For flaw detection inspections, both test probes of a dual differential instrument are placed on the same test object and scanned over the surface of the test object. When the two test elements are over a homogeneous flaw-free area of the test item, there is no differential signal developed between the elements since they are both inspecting identical material. However, when first one and then the other of the two test elements is passed over a flaw, a large differential signal is produced. The dual differential flaw-detection instrument has a high degree of sensitivity, stability, and resolution. Yet, it is independent of the type of material and the metallurgical properties of the material being tested.

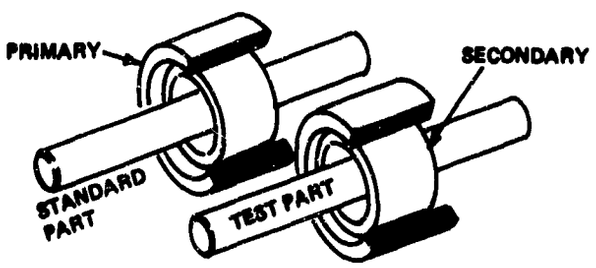
The absolute type of eddy current instrument is characterized by the ease of operating a single test coil or probe, and by being adjustable to minimize the effect of variations in part-to-probe spacing and angle. This adjustment is generally called lift-off compensation. In the absolute type of eddy current instrument, the test probe is part of a resonant circuit. The signals obtained from such a circuit, both when the probe is placed on a test item and when it is placed a small distance from a test item, are shown in Figure 47. The intersection of these two curves define the so-called lift-off point, i.e., the point at which there is no signal difference due to the variation in relative probe location.

ABSOLUTE TECHNIQUE

A COMPARISON OF IMPEDANCE VARIATIONS BETWEEN THE TEST PART AND A FIXED STANDARD (EITHER ELECTRICAL OR AN EXTERNAL PART)

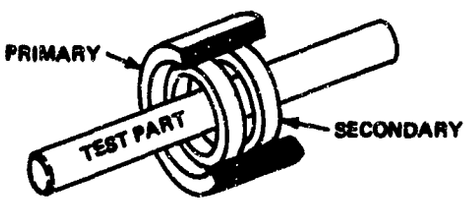


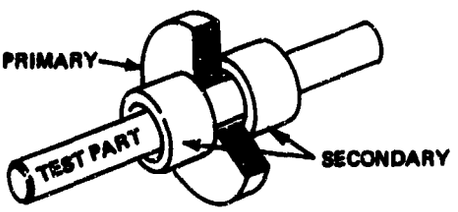


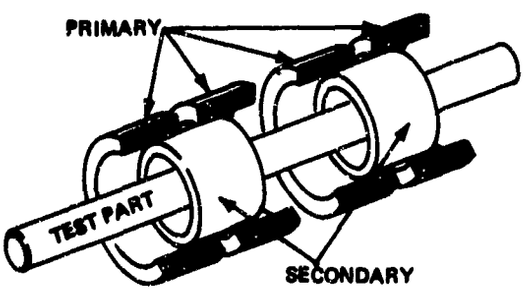


DIFFERENTIAL TECHNIQUE

A COMPARISON OF IMPEDANCE VARIATIONS BETWEEN ADJACENT SECTIONS OF THE SAME TEST PART







READOUT METHODS:

VARIOUS TYPES OF READOUT DEVICES ARE AVAILABLE INCLUDING METER, SCOPE, PEN, RECORDER, FLASHING LIGHTS, AUDIBLE ALARMS, COUNTERS, AUTOMATIC MARKING AND SORTING. USE ANY ONE OR ALL AS BEST SUITS THE PARTICULAR APPLICATION.

FACTORS WHICH AFFECT THE ELECTRICAL CHARACTERISTICS OF THE PICK-UP COIL:

TEST PART:	TEST SYSTEM:
1. CONDUCTIVITY	1. FREQUENCY
2. PERMEABILITY	2. COIL SIZE
3. MASS	3. CURRENT
4. HOMOGENEITY	4. SPACING (COUPLING)

Figure 46. Coils for Absolute and Differential Techniques of Eddy Current Testing

The test probe circuit produces an output signal characteristic of the particular probe-to-object distance involved in a given test. If this spacing should change during the test, the variations in output would affect the resultant accuracy. Therefore, compensating the instrument for a range of probe-to-object spacings is desirable. This is accomplished by determining the lift-off point over a selected range. The lift-off point is defined as the common balance point of the instrument for two probe-to-object distances. (See Figure 47.)

Compensating an instrument for a given lift-off variation minimizes changes in instrument output for a range of part-to-probe spacing variations. However, it is very important that the range of part-to-probe spacing variations be properly selected. The best lift-off characteristics are obtained by compensating the instrument for the spacing variation which will be encountered during the test. Various systems and equipment have been developed or proposed for overcoming the problems caused by the lift-off effect. Although the lift-off effect problems have been solved sufficiently for many valid tests, development in this area is continuing.

The ease of operation of an absolute type of instrument, as well as its ability to be compensated, are its most favorable characteristics. These characteristics make this type of instrument ideally suited for inspections which will be performed manually. It can be used for inspections involved in material receiving, low volume samplings, and for detecting flaws in irregularly shaped objects.

d. Test Display Systems. The eddy current signals obtained from both the dual differential and absolute instruments can be displayed by meter or oscilloscope. The simplest is the meter display, which provides a numerical

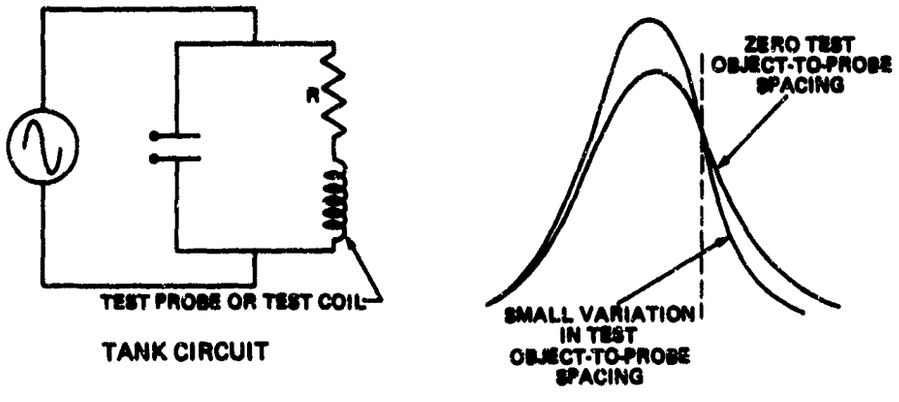


Figure 47. Eddy Current Test Probe Circuit and Plot Showing Lift-Off Point

indication of the scaler difference between the test objects. When used with a flaw detection type of instrument, this numerical indication may be calibrated to roughly approximate the depth of the flaw. The oscilloscope, of course, indicates more information than the meter regarding differences between the test items.

It is possible to pick one or more values on the instrument meter which, if exceeded, will produce an electronic signal that will operate a mechanical device to reject the test object from a production line.

e. Test Configurations and Applications. A very significant part of any system used to inspect test objects using the eddy current method in an industrial environment is the mechanical equipment associated with the electronic instrumentation. The mechanical system must present the test object to an inspection station, provide the part-to-probe orientation and motion, and segregate the acceptable test objects from the rejectable test objects based upon the "decision" of the eddy current instrument.

For evaluations of such test item characteristics as hardness, case depth, alloy, and geometrical variations, the test objects are generally passed through the inside of a coil. The test objects may be either dropped through the coil at a free-fall rate, or moved through it on a conveyor belt — depending on the speed capabilities of the test instrument. Ideally the test rates obtained from such electromechanical systems vary from 1,000 parts per hour to 35,000 parts per hour, depending upon the instrumentation used and the size and geometry of the test items.

For automated flaw detection systems, it is necessary to provide a relative motion between the test item and the test probe so that the test probe (or probe pair) can scan the surface of the test item. Because the flaw detection probe is generally small, the entire test object usually cannot be inspected at one time. The relative part-to-probe motion for symmetrical objects may be obtained by either rotating the test object before a stationary probe, or by rotating the probe about the test object.

For example, a bar may be tested for longitudinal seams and cracks by rotating and traversing the bar on a set of drive rollers with the test probe held stationary near the surface of the bar. Or, the bar may be inspected by passing it through a test probe which circles the bar.

In summary, eddy current NDT has developed into one of the major test methods used in industry today. The variety of instrumentation available makes eddy current testing applicable to a great number of production jobs. Also, test instrumentation can be easily integrated into automated manufacturing lines.

50. COIL ARRANGEMENTS

a. General. The key element of the eddy current sensing system is the test coil. Since test item configurations come in many shapes and sizes, the coils used are designed to conform to these configurations.

b. Test Coil Arrangements. Test coils can be arranged around the test item, inside of it, or on its surface. In each case, the type of coil used can be a single winding or a double winding. (See Figure 48.)

(1) Surface Coil Arrangements. A surface coil (see Figure 48) is designed for use on the test item surface. For maximum effect, this coil must fit the contour of the surface. The coil can be contacting or non-contacting, operator held, or automated.

(2) Shielded Gap Coil. Shielding may be provided for the probe as shown in Figure 48.

(3) Spring-Loaded Coil. To minimize lift-off effects which can cause difficulty in obtaining meaningful indications, spring-loaded coils, such as the one that was shown in Figure 48, are often used. The spring type coil maintains constant contact with the test item surface and insures that this contact has a constant pressure. Such coils can also be designed to hold the coil a specific distance above the surface of the item.

(4) Spinning Coils. Figure 48 also illustrates the use of a surface coil mounted so that the coil can be rotated about the circumference of the article. Often, both the encircling coil and the spinning coil are used to insure complete coverage of the area of interest. The coil may be stationary and the test item rotated and traversed.

c. Inside Coil Arrangement. The inside coil is similar to the encircling coil but is designed to be placed inside the test item as shown in Figure 48. Inside surface coils can be constructed with remote controls which permit positioning the coil at specific spots on the inside of tubing.

d. Encircling Coil Arrangement. The encircling coil (Figure 49) is used to enclose a test item about one of its axes to give the maximum effect. This coil must be shorter than the test item to reduce end effect. The shape of the coil is not always circular. A coil produces the maximum effect if it closely coincides with the surface of the item being tested.

e. Gap Probe. The gap type of probe uses magnetic material to shape the magnetic field to enhance the test item's effect on the induced eddy currents (similar to a recording head). The probes can be either single or differential coils. The gaps involved typically are 0.015-inch wide by 0.125-inch long. This probe may also be used to follow varying surfaces of the article, which tends to make it widely used for nonuniform shapes.

f. Focused Coils. The focused coil's magnetic field is specially shaped or focused by the method of winding. (See Figure 49.)

g. Wide and Narrow Encircling Coils. Wide coils cover large areas, so they respond mostly to bulk effects, e.g., conductivity; narrow coils sense small areas and will respond to lesser effects, such as flaws. (See Figure 49.)

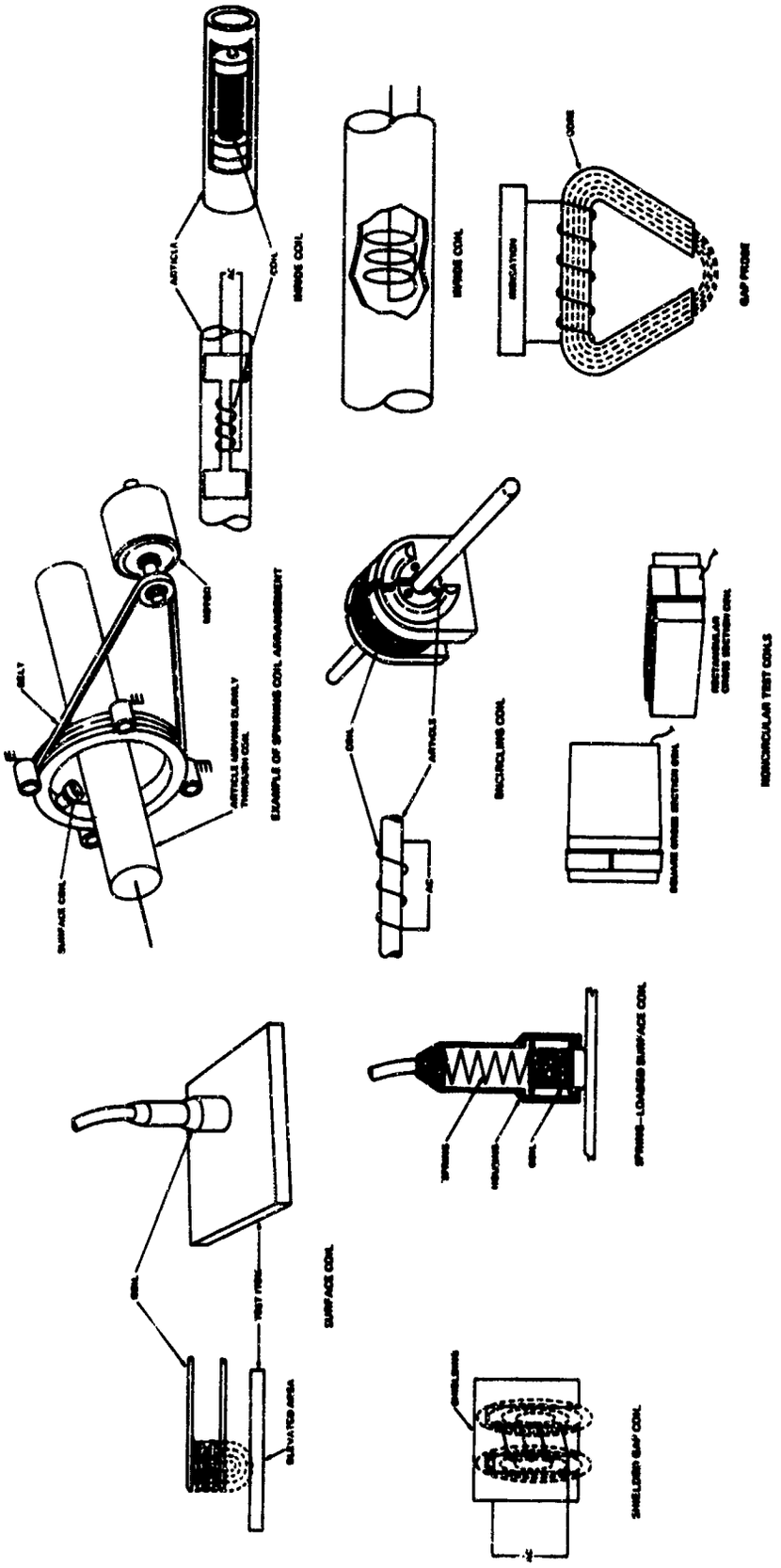
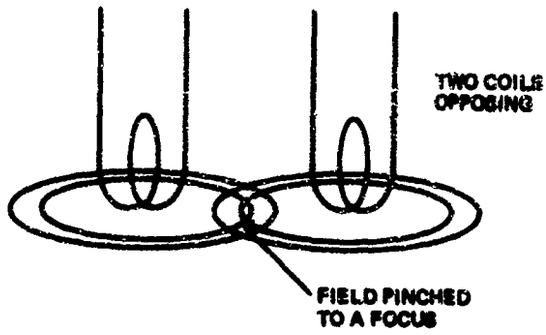
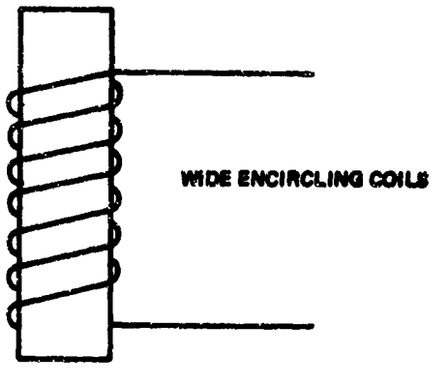
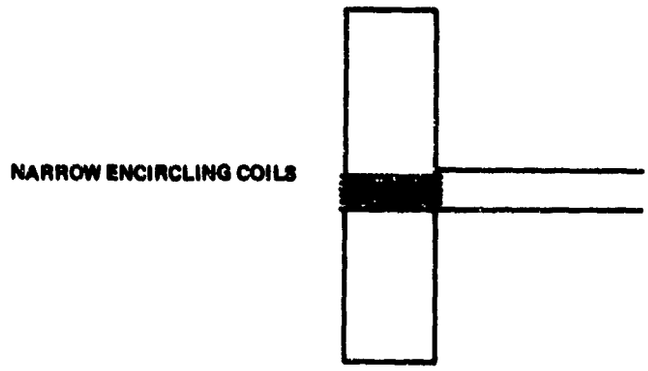


Figure 48. Coils For Electromagnetic Testing



FOCUSED COILS





WIDE AND NARROW ENCIRCLING COILS

Figure 49. Focused and Encircling Coils for Electromagnetic Testing

51. TEST SETUPS

a. General. Because so many techniques and variations of these are available with eddy current testing, the approach here is to select highlights of several common techniques. Figure 50 illustrates a technique which uses one area of the test item as a reference standard against which another area on the same item is compared. In this technique, it is assumed that a flaw will not extend over both areas or that if a flaw extends over both areas, it will be oriented so that a difference will still be reflected in the indication. This arrangeme . is known as the self comparison technique.

Another coil arrangement (also shown in Figure 50) illustrates a coil being used for external comparison. It is similar to the self-comparison technique except that it is set up with a carefully chosen, flaw-free test reference held stationary in one coil while the item being tested is moving through the other coil. A comparison is made with the reference standard. No indication is observed, of course, unless a flaw appears in the test item being examined. If a flaw passes through coils, it causes a coil impedance change. (See Figure 51.)

b. Impedance, Reactance, and Feedback-Controlled Testing.

(1) Impedance Testing. This technique senses (and indicates on a meter) the magnitude of the coil impedance changes caused by flaws in the test item. Generally speaking, most flaws such as cracks, holes, inclusions, porosity, or dents affect the coil impedance. An important factor to remember is that the indication in impedance testing will not identify which property of the test item caused the impedance change. It could be conductivity, dimension, or permeability.

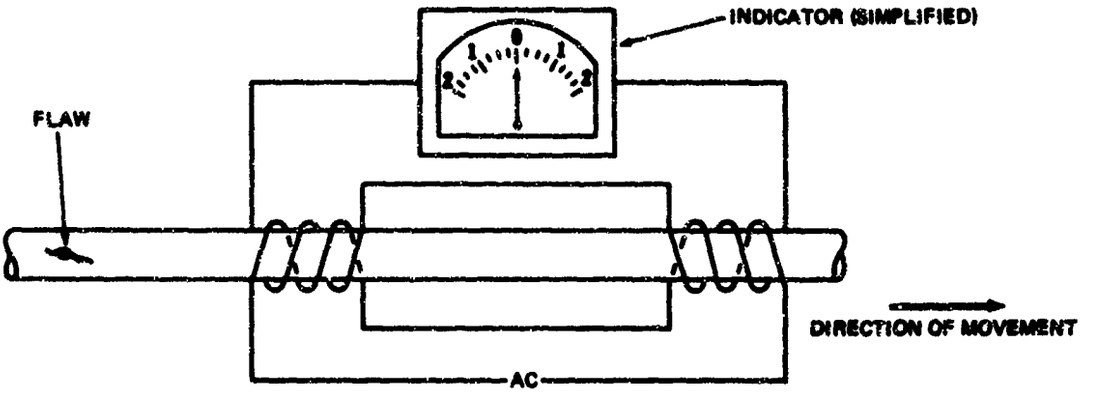
(2) Reactance Testing. In this technique, the reactance of the coil changes when a flaw is detected in a test item. This reactance change alters the oscillator frequency at the test coil. Neither impedance testing nor reactance testing can distinguish between or separate the three main variables (conductivity, permeability, and dimension).

(3) Feedback-Controlled Testing. This technique senses changes in the inductance/resistance.

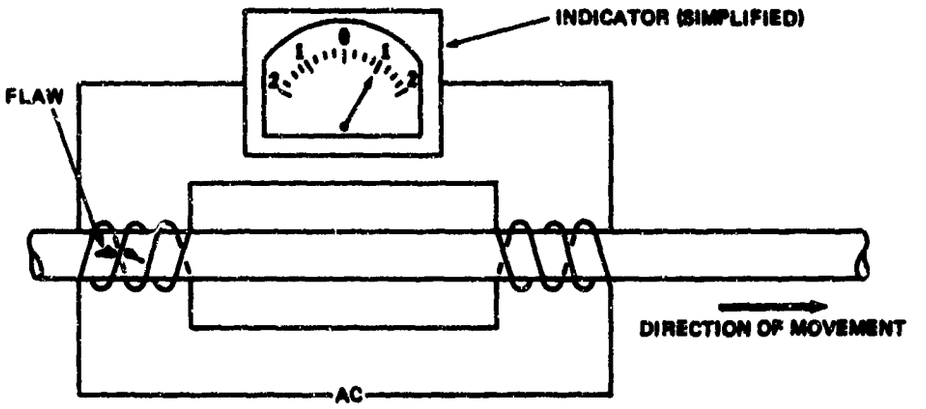
52. FLAW DETECTION

A major application of eddy currents is the detection of flaws. In such detection, eddy currents flow in regular patterns within a test item and a flaw changes this pattern. As the pattern changes, the output indication changes.

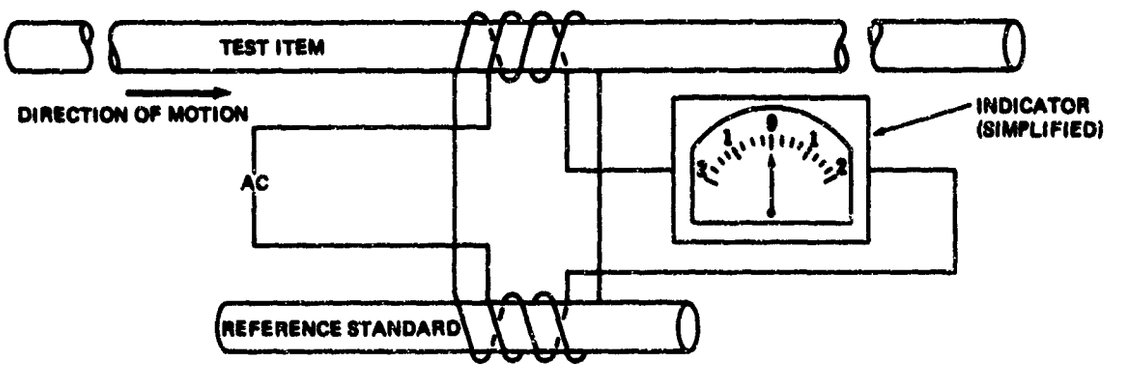
Detection of flaws depends directly on the design of the specific types of eddy current detectors. It also depends directly on whether manual or automatic methods are used. A typical eddy current flaw detector instrument panel is shown in Figure 52. In using this detector, it should be recalled that the detector does not provide absolute measurements. If the test item's



DIFFERENTIAL COILS



SELF-COMPARISON COILS



EXTERNAL COMPARISON ARRANGEMENT

Figure 50. Eddy Current Test Setups

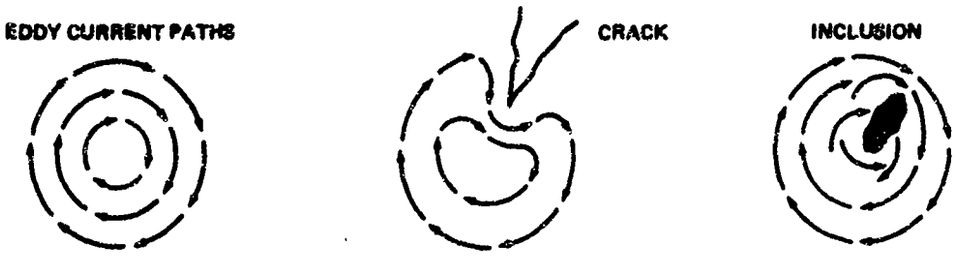


Figure 51. Eddy Current Pattern Changes Caused by Flaws

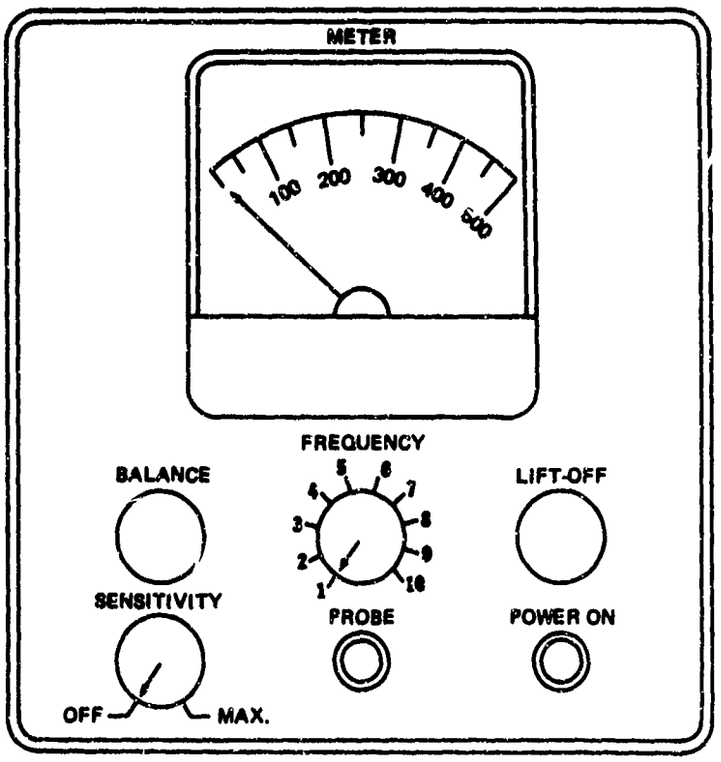


Figure 52. Typical Impedance (Flaw) Detector

characteristics are constant, the meter indication is constant. On the other hand, a change in test item characteristics will change the coil's impedance which, in turn, will cause a change in the meter indication.

53. INTERPRETATION OF RESULTS

In order to perform quantitative eddy current tests, four basic steps must be followed: (1) a basis must be established for selecting the eddy current method of testing; (2) control must be established over the electromagnetic field to obtain the maximum amount of interpretable information; (3) valid data must be obtained; and (4) the data must be accurately interpreted to obtain the desired information about the test item. The failure to perform any one of these steps adequately will result in a poor test.

54. EDDY CURRENT CALIBRATION REFERENCES

a. General. As in other forms of nondestructive testing, reference standards are required. However, these are not available for eddy current testing from national standardization sources. Therefore, the references must be obtained or fabricated for each specific task and generally consist of materials with known characteristics. In some cases, the reference standard is an article with known chemical or alloy composition characteristics and no significant flaws. This reference standard is used as a basis for comparison. In other cases, artificial or natural flaws are intentionally added to a reference standard so that it can be used in equipment calibration. When an external reference is needed, the reference item must have all the characteristics of an acceptable item. Reference standards with known flaws are also used to verify the sensitivity of equipment as well as the overall performance of a testing system.

b. Artificial and Natural Calibrated References. It is common practice to specify eddy current testing performance in terms of reference standard articles with flaws which can be duplicated and described by written procedures. Both artificial and natural flaws can be described and used as reference standards.

An artificial reference standard can be prepared by selecting an item of the same composition, history, and dimensions as the items to be tested. The reference item should not contain significant inherent flaws. Artificial flaws can then be introduced to simulate longitudinal notches, circumferential notches, drilled holes, file cuts, pits, diameter steps, and indentations. Natural flaws can be developed or accumulated. For example, cracks can be developed by submitting a material to cyclic stress until a natural fatigue crack is generated. This can then be machined to produce a surface or hole crack of known depth. Specimens with natural flaws can be accumulated over a period of time during routine testing of articles. These natural flaws can then be processed to provide reference standards.

55. PERFORMANCE AND CALIBRATION REFERENCE STANDARDS

a. General. Articles can be classified as performance reference standards or calibration reference standards, depending upon how the article is used.

b. Performance References. A performance reference standard is used to qualify a test system for a particular test. It is normally used at the beginning of the test to insure that all controls are properly set and that the system performance is normal. The item is prepared with a range of flaws to insure that the system can detect the variables of interest.

c. Calibration References. The purpose of a calibration reference standard is to insure that the amplitude and phase characteristics of a test system does not drift during continuous testing. When the test equipment is used for extended periods of time, the calibration of some components may change. Periodically, the calibration reference standard is passed through the testing system to verify that the equipment is still calibrated and that amplitude and phase are stable. The types of flaws and their location in the calibration reference standard are not the same as those in the performance reference standard because their function differs as test references.

56. ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Tests can often be made from one side of the test material.

(2) Tests are readily adapted to remote readout.

(3) Test probes and coils can be made to withstand extreme temperature and environmental conditions.

(4) Electromagnetic tests are adaptable to high-speed scanning and automatic feedback.

(5) Tests can be used to measure plate or tubing thickness.

(6) The thickness, continuity, and conductivity of a thin conductive coating on nonconducting surface can be determined.

(7) Tests can be used to measure the thickness of nonconducting coatings on conducting base materials.

(8) Because electromagnetic tests are highly sensitive to different structural and compositional properties of materials, many applications of these tests are possible if most of the properties are controlled or known.

(9) Tests can be automated by the use of magnetic tape recorder pick-up devices or Hall elements to provide direct electrical output signals.

(10) High-speed scanning of large structures can be accomplished with the proper magnetizing and readout equipment.

b. Disadvantages.

(1) Because of high sensitivity to changes in the structural and compositional characteristics of an object, electromagnetic tests can be ambiguous unless the variations (such as hardness and geometry) are controlled or known.

(2) Electromagnetically-induced eddy currents tend to flow in paths parallel to the material surface. Therefore, these tests are insensitive to poor bonding of coatings and flaws parallel to the surface of the material.

(3) Since eddy currents are concentrated near the surface of a conductor, these tests are more sensitive to the surface than to the interior of a conductor.

(4) Processing and heat treatment influence the electrical conductivity of the test item. (For sorting purposes, this is an advantage.)

(5) Since electromagnetic tests are sensitive to material property averages, flaws are not detected unless they substantially interrupt the flow of current.

Section IX. CONDUCTIVITY NDT

57. BACKGROUND

Electrical conductivity NDT is another form of electromagnetic testing involving the interaction of magnetic fields and circulating currents. Here, currents are introduced in a test item by means of special probes and the resulting magnetic fields are measured with special sensing equipment. This method is widely used for the testing of tubing.

Electrical conductivity can be an important indication of the condition of nonferrous metals. For example, it indicates the degree of purity of unalloyed metals. The magnitude of the electrical conductivity is of special significance to the electrical industry. For age-hardenable aluminum and titanium alloys, electrical conductivity is a measure of hardness. Mixed alloys can often be sorted by conductivity measurements. Segregation effects can frequently be indicated by the curve of the conductivity over an entire metal block.

58. EQUIPMENT

There are relatively few nonferrous alloys having similar or overlapping conductivity. Therefore, in most cases, the conductivity is representative of the alloy.

The probe coil instrument is generally used for the following tests (see Figure 53).

(1) Determination of electrical conductivity of test items made of copper, aluminum, and alloys of these.

(2) Determination of degree of purity of metals.

(3) Sorting of mixed metal alloys.

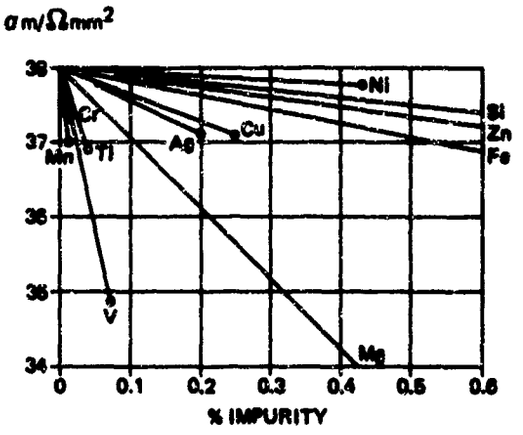
(4) Hardness measurements of alloys where this property has an unequivocal relationship with electrical conductivity.

On a typical control panel of a conductivity meter, the control knob is adjusted until the pointer of the indicating instrument rests at the zero point in the center of the scale. (See Figure 53.) The absolute value of the electrical conductivity can then be read directly on the large conductivity scale. Thus, the electrical conductivity can be measured in only a few seconds. The only test item access required is a flat surface on the part, of approximately 0.4 inch maximum diameter.

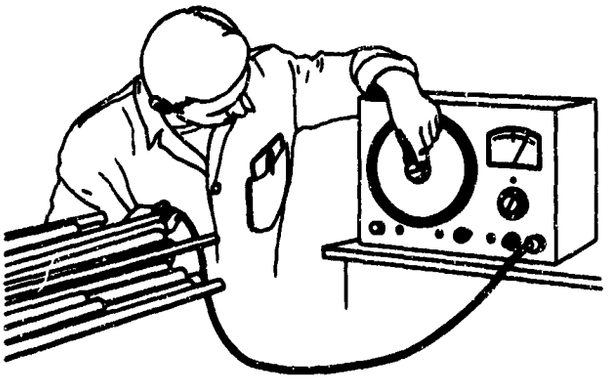
In addition to determination of the electrical conductivity, the meter deflection method is used for the rapid sorting by conductivity value (i.e., for hardness, purity, alloy). For this the pointer of the meter is adjusted to zero for the average value of the desired conductivity range. When the electrical conductivity deviates from this average value, a deflection is obtained either in the positive or negative direction, according to the increase or decrease in conductivity from the value which results in a zero deflection. By means of the sensitivity control, the tester can select the sensitivity so that a specific deflection (for example, ten scale divisions) is attained. Sorting can be performed rapidly because the tester observes only the deflection on the meter when the probe coil is placed on the part, which requires approximately one second. Thus, it is possible to rapidly sort production parts according to conductivity.

If a low sensitivity is selected, the entire conductivity range can be controlled on the scale of the zero meter. This is of significance, for example, for a rapid scrap sorting for alloys which cover a very large conductivity range and must be separated and sorted according to alloy groups.

In hardness testing, the sensitivity can be adjusted so that a positive or negative deflection of one scale division corresponds to a hardness variation of one Brinell unit, for example.



INFLUENCE OF METALLIC ADDITIVES ON THE CONDUCTIVITY OF ALUMINUM



TESTING RODS OF MIXED ALLOYS BY APPLYING THE PROBE COIL TO THE ROD ENDS

Figure 53. Conductivity Instrument and Graph Showing the Influence of Aluminum Impurities on Conductivity

59. TECHNIQUES OF TESTING

a. General. Testing of mixed lots is generally performed by the relative technique, i.e., by observing deflections on the zero meter of the conductivity test instrument. Only in rare cases is the absolute technique used, i.e., reading the actual conductivity value on a calibrated scale.

b. Indirect Hardness Measurements. The hardness of age-hardened aluminum has an unequivocal relationship with conductivity and therefore can be easily determined using the conductivity test instrument. Thus, indirect or relative hardness measurement with the conductivity test instrument has become a widely used technique. The test speed is many times faster than that of any other hardness test. In using this technique, the tolerance range is adjusted on the zero meter of the instrument by means of reference test items for which hardness has already been measured mechanically.

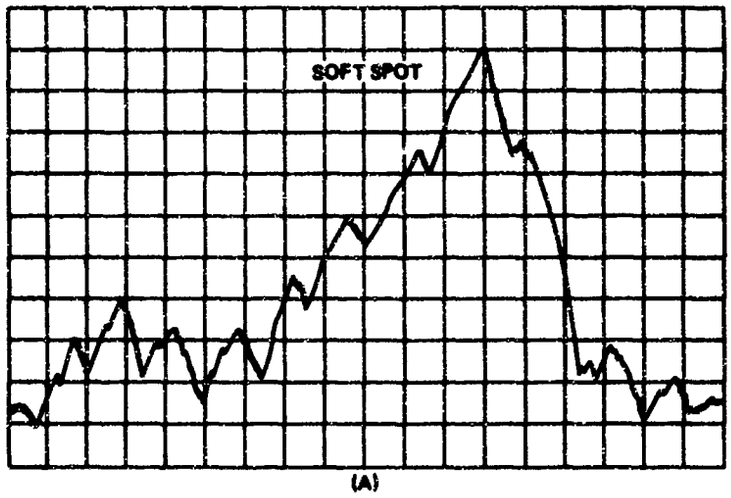
Indirect hardness measurement is also used to reject overheated test items, or those items quenched at too high a temperature. These can be eliminated as a result of their low conductivity. By using a conductivity test instrument, a specified quenching temperature and specified hardness can be attained much more accurately than by use of conventional methods of measuring Brinell hardness.

The conductivity test instrument is also used to control the uniformity of hardness on semi-finished test items such as rods, sheets, extruded shapes, and tubes. When a large number of parts are quenched simultaneously, areas termed soft areas sometimes appear if the items are not uniformly quenched. (See Figure 54.)

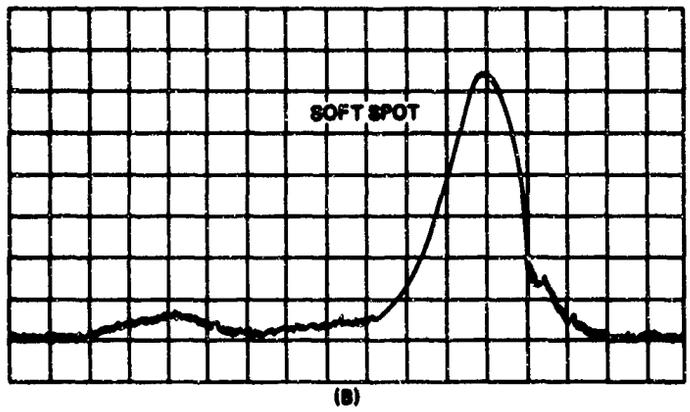
This same type of defect sometimes appears on extruded articles that are quenched immediately after being extruded. For the inspection of extruded test items, a search coil is moved along the extrusion. Testing for soft areas requires considerably less time than Brinell impression testing. A special conductivity probe coil is available to detect soft spots quickly on large sheet metal surfaces. Figure 54 showed the indications resulting from using a conductivity instrument to test for soft spots in sheet metal. Special provisions can be made for suppression of the lift-off effect as shown in the "B" portion of the figure so that only conditions such as soft spots are indicated.

60. STANDARDS FOR ELECTRICAL CONDUCTIVITY TESTING

International Annealed Copper Standards (IACS) are available for use in calibrating electrical conductivity instruments. These IACS standards may be supplemented by secondary standards to provide a means of converting some relative type measurements into absolute. (A method for accomplishing this is described in Materials Research and Standards, November 1968, pp 8-15.) These secondary standards can be fabricated so that they are correlatable to the national standards available.



(A)



(B)

INDICATIONS OF A SOFT SPOT IN SHEET METAL:
(A) WITHOUT SUPPRESSION OF THE LIFT-OFF EFFECT. THE PERIODIC DEFLECTIONS ARE CAUSED BY IRREGULAR MOVEMENT OF THE WHEELS OF THE TRAVELING COIL.
(B) WITH SUPPRESSION OF THE LIFT-OFF EFFECT.

Figure 54. Indications of Soft Spots with Conductivity Instrument

A typical modern conductivity meter used to inspect nonferrous alloys is calibrated by adjusting to the values of two reference standards provided by the instrument manufacturer. These standards are usually near the 12 and 100 percent IACS values and correspond to calibration marks on the instrument dial. The use of only two reference standards for calibrating the instrument near the scale ends has been found to be inadequate by some testers who require a high degree of accuracy traceable to national measurement standards (e.g., airframe manufacturers). It has been pointed out that the two reference standards could allow the instrument to be in error relative to its scale markings and the instrument readings would be unstable.

Many engineering process specifications require that test measurements be both accurate and traceable to national measurement standards. Objective evidence of such traceability is not generally provided by instrument manufacturers. Also, the National Bureau of Standards does not offer a service for the calibration of these meters or electrical conductivity standards. The secondary standards provided by some companies can be used to solve this problem. Such standards have allowed airframe companies to meet the requirements of MIL-A-22771 (ASG) "Aluminum Alloy Forgings, Heat Treated," which requires an accurate determination of a cut-off point (in percent IACS) below which aluminum forgings are to be considered unsatisfactory. ASTM Method of Test for "Resistivity of Electrical Conductor Materials" (B93-65) has been used as a guide for processing the material necessary to produce such secondary conductivity standards so that they can be directly read in percent IACS.

The foregoing guidelines have been included here because: (1) conductivity standards are not currently available commercially; and (2) the National Bureau of Standards does not provide a calibration service or standards for use of conductivity meters.

61. ADVANTAGES AND DISADVANTAGES

a. General. The conductivity type of nondestructive testing offers a great advantage in the speed available. However, the flaw size and location are not indicated.

b. Advantages.

(1) Only a flat surface of the test item approximately 0.4 inch in diameter is required for test access.

(2) Lightweight portable instruments are available.

(3) Rapid sorting may be accomplished.

(4) In hardness testing, the sensitivity can be adjusted so that a positive or negative deflection of one scale division corresponds to a hardness variation of one Brinell unit, for example.

c. Disadvantages.

(1) Does not indicate size of flaws present.

(2) Does not indicate specific location of flaws.

Section X. MICROWAVE NDT

62. BACKGROUND

Microwave NDT utilizes electromagnetic radiation with frequencies between those of radio waves and infrared (approximately 1 to 100 billion Hertz — or 1 to 100 gigahertz).

An important characteristic of microwaves in NDT is that they follow the laws of optics and they may be used to test nonmetallic materials. They travel in straight lines and can be reflected and refracted. They interfere and scatter according to the laws governing light rays. Differences from light waves exist in that microwave wavelengths are typically in the range of 1 inch (which is approximately 100,000 times greater than light wavelengths). Microwaves therefore interact with solid objects in a manner similar to the way that light waves interact with microscopically thin films, smoke particles, and the like. The use of microwaves in NDT is a considerably later development than radiography, for example, and during this discussion it should be remembered that much of the microwave NDT technology is still in the developmental stage.

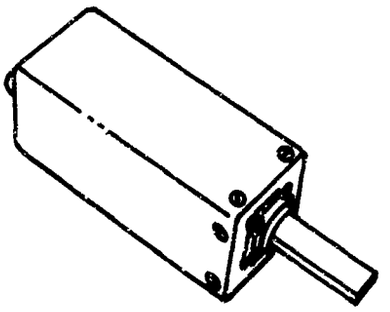
Microwaves penetrate most nonmetallic opaque materials and structures, reflecting and scattering from internal flaws and boundaries and interacting with the molecules of the material.

Flaws such as cracks, inclusions, voids, and unbonded areas can be detected in many nonmetallic parts and structures by either microwave reflection or microwave scattering techniques.

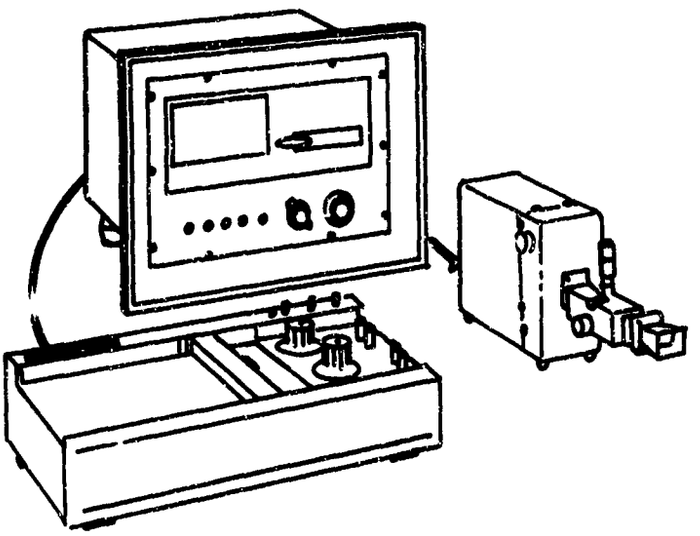
63. MICROWAVE REFLECTION EQUIPMENT

a. General. The equipment needed for microwave reflection measurements includes a system incorporating some form of microwave reflectometer. A typical system is shown in Figure 55. The basic instrument cabinet serves as an analyzer and display unit. The reflectometer portion of the system is the smaller unit. When this unit is connected to the basic instrument cabinet, the meter indicates the amount of energy reflected by the test item and allows reflection measurements.

A typical testing procedure for detecting an unbonded area in a layered structure is to zero the reflectometer on a normal (properly bonded) portion of the structure. The reflectometer head is then scanned over the test part, either manually or mechanically. An unbonded area with a separation of



BASIC MICROWAVE REFLECTOMETER



PHASE AMPLITUDE REFLECTOMETER
(AT RIGHT) CONNECTED TO ANALYZER
UNIT (TOP) AND XY-RECORDER

Figure 55. Microwave Equipment

0.001 inch, for example, results in a change in the reflected energy (and, therefore, a departure of the indication from zero). In most cases, this departure is quite pronounced and easily recognizable as an "error" signal. However, the separation is necessary to produce such an indication.

To automate the measurement, it is possible to add an alarm system which signals the presence of defective areas whenever the reflectometer signal exceeds a predetermined level.

The microwave reflectometer technique has been used to detect unbonded areas in such diverse products as glass fiber resin impregnated honeycomb panels and automobile brake shoes.

b. Phase-Amplitude Reflectometer. The single reflectometer measures changes only in the amplitude of the reflected signal. More complete information about the test item can be obtained by sensing both the amplitude and phase of the reflected energy. This can be done with a special type of reflectometer called a phase-amplitude reflectometer illustrated in the right hand bottom portion of Figure 55. This reflectometer has a two-dimensional output. When it is connected to the basic instrument cabinet and an XY recorder (as shown), the amplitude and phase of the microwave beam reflected by the test part are displayed graphically and continuously on paper. Amplitude is plotted radially while phase is plotted circumferentially.

Since amplitude and phase contain all of the test information that can be extracted from a test part by reflection at a particular frequency, the polar display presents a two-dimensional graph of the test variables in the test item. Recorder response is virtually instantaneous, permitting a continuous plot of varying conditions as the test part is scanned.

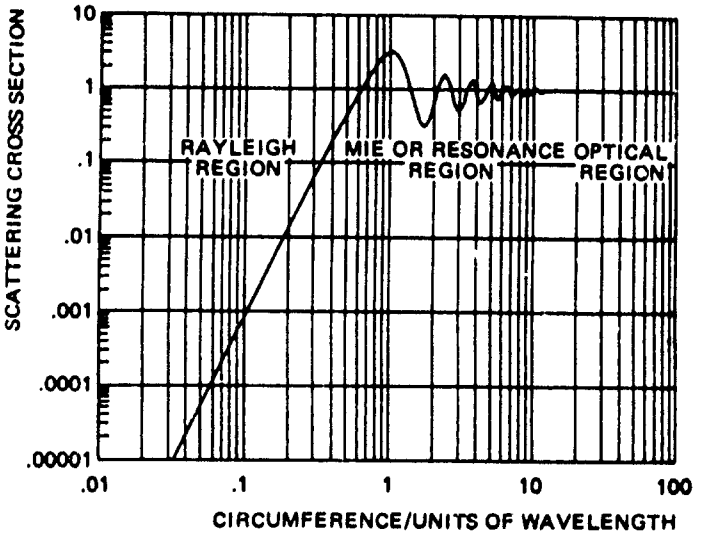
If a test variable (e.g., flaws, thickness, dielectric properties) varies continuously, a curve will be traced out by the recorder. If the variable changes in discrete steps, a sequence of ink dots results. Since different variables go in different directions on the chart paper, many measurements may be plotted on the same chart to facilitate calibrations, provide a permanent record, or permit comparisons.

By adding a phase shifter, adjustments can be made so that the basic instrument meter will sense the component of the reflected signal at a particular phase angle. This technique, is termed "phase analysis," a term borrowed from eddy current testing because the same principle is involved. It may sometimes be used to suppress the influence of an undesired test variable over a limited range.

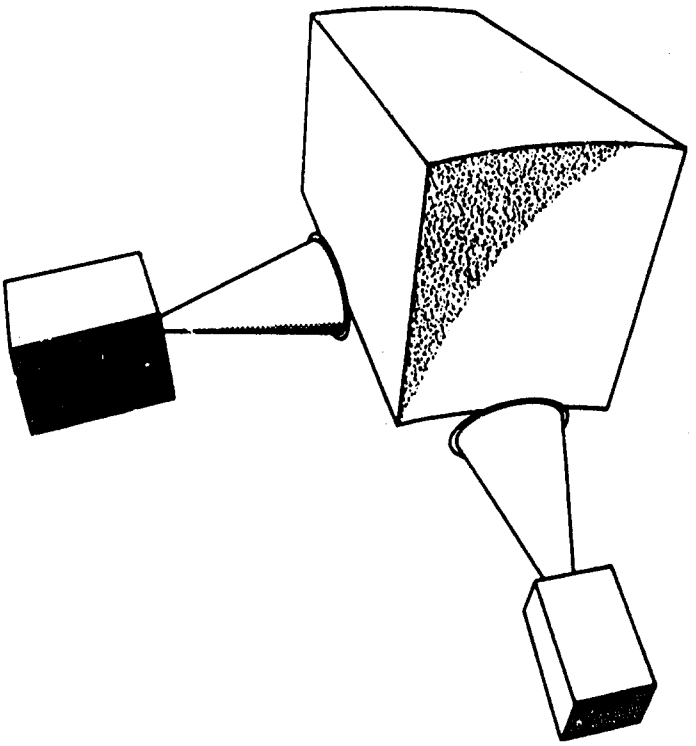
64. FLAW DETECTION BY SCATTERING

Flaws such as cracks, voids, inclusions, and foreign matter in large bulk test items serve as scattering centers of microwaves and can sometimes be detected effectively by sensing microwaves that are scattered sideways from the main beam passing into the object. The amplitude of the microwave energy scattered by a flaw is a function of the flaw diameter and the microwave wavelength.

At very low microwave frequencies (long wavelengths), scattering power is low and varies as the fourth power of frequency. This is the Rayleigh region. As the microwave wavelength approaches the diameter of the void or inclusion, the Rayleigh law no longer applies and scattering enters an oscillating region known as the Mie or resonance region. At still higher frequencies, scattering cross section remains constant. This is known as the optical region (See Figure 56.)



SCATTERING CROSS SECTION OF SPHERICAL DEFECT VERSUS RATIO OF CIRCUMFERENCE TO WAVELENGTH



TRANSMITTER–RECEIVER SETUP FOR FLAW DETECTION BY SCATTERING TECHNIQUE

Figure 56. Microwave Scattering Technique

As a practical example, voids have been detected in polyurethane blocks and structures up to several feet thick by positioning a microwave detector pointed at right angles to the microwave beam traversing the test part as shown in Figure 56.

A basic microwave analyzer-display cabinet and some of the different microwave probes (antennas) developed for use with a system are shown in Figure 57. The different wave guides produce microwave fields of different shape and range, as required by the various applications desired.

65. MICROWAVE INTERFEROMETRY

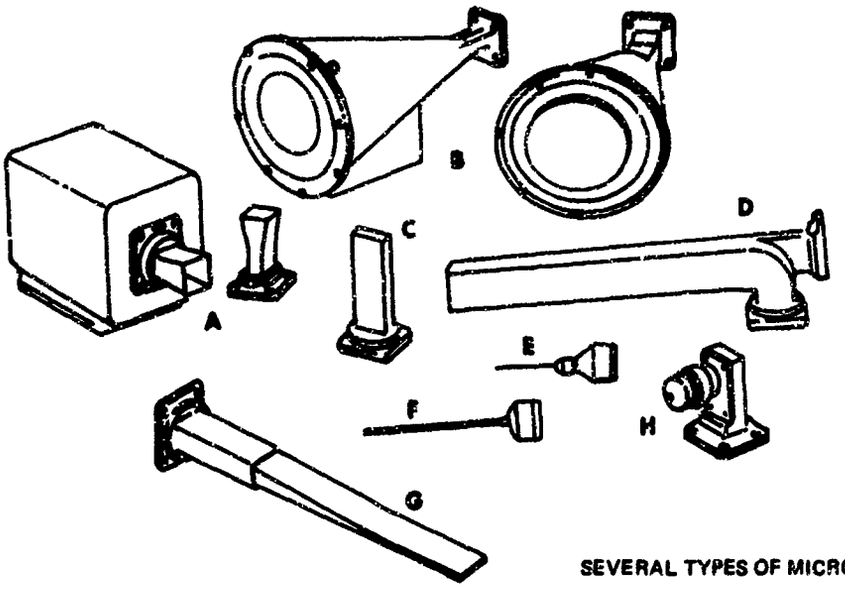
a. General. Wave interference occurs whenever two or more sets of wave trains simultaneously pass through a given region. The result of the interference of the two waves is called a standing wave.

An example of this principle can be demonstrated by observing the brilliant colors that are often seen when light is reflected from the surface of a soap bubble or from an oil slick, and which are produced by the interference between two trains of light waves; the first train reflected at the top surface of the soap or oil film, and the second reflected from the bottom surface. Because phase differences depend on wavelength, some colors experience destructive interference and others constructive interference, depending on film thickness. The color seen at a particular point in the film is the result of constructive interference. The same thing in principle occurs when microwaves strike objects which to them are "thin films."

Interference does not require two reflecting surfaces. A single reflecting surface, such as a metal surface, will do. When a microwave strikes such a reflecting surface, it is reflected back on itself, producing two waves traveling in the same space in opposite directions, creating a condition where interference will occur.

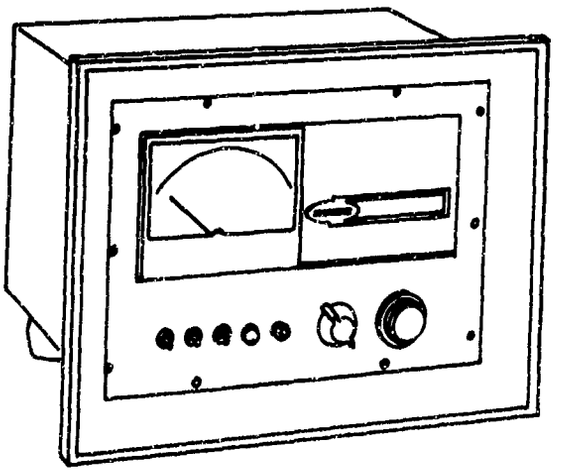
b. Distance, Dimensions, and Contour. Practical applications of microwave interference phenomena use two types of microwave reflectometers for flaw detection; i.e., the simple reflectometer and the phase-amplitude reflectometer. (Refer to Figure 55.) Each serves equally well as a microwave interferometer. If either of these units is set up so that the microwave beam falls on a reflecting surface (either metal or nonmetal) located some unknown distance away from and in front of the antenna from which the microwave beam emerges, the distance to the reflecting surface can be very accurately gaged. Related applications are measurements of contour, out-of-roundness, motion and displacement, involving either metal or nonmetal parts. Measurements can generally be made over distances from 0.001 inch to several feet with a high degree of accuracy.

A unique feature of microwave interferometers is the fact that measurements can be made through intervening nonmetallic structures. For example, measurement can be made through a window in an oven wall with the test item located in the oven to determine some of the characteristics of the test item at high temperatures.



SEVERAL TYPES OF MICROWAVE PROBES (ANTENNAS):

A. RECEIVER WITH TWO SMALL PICKUP HORNS
B. TWO OVAL HORNS WITH TWO MICROWAVE LENSES
C. LONG FIELD PROBE
D. CURVED--FIELD PROBE
E. HYPODERMIC NEEDLE PROBE
F. DIPOLE
G. DIELECTRIC ROD ANTENNA
H. SHORT--FIELD PROBE WITH SAMPLE HOLDER



ANALYZER--DISPLAY PORTION OF MICROWAVE TESTING SYSTEM

Figure 57. Microwave Probes and Test Equipment

If the distance to the target is great, a probe different from those illustrated on the units that were shown in Figur 56 would have to be used. Those probes in Figure 56 are useful for making measurements over distances up to about 1 inch. Figure 57 shows oval horns which are about 9 inches long and are capable of sending a collimated microwave beam over distances of 20 feet or more. Even at the relatively great distance of 20 feet, a change in the position of a reflecting surface of a few thousandths of an inch can be sensitively detected and measured. The technique for doing so is almost identical to the technique for flaw detection. The reflectometer is adjusted to give zero output when the reflecting surface is in a known position. Any deviation from this position will then result in a meter deflection at a predetermined amplitude.

Precise measurements of such distances are often needed in machining operations, particularly when large structures are being machined. It is possible, for example, to determine the dimensions or contour of a wide variety of shapes as large as a rocket motor bulkhead.

c. Vibration Measurements. A corollary of distance measurement is vibration measurement. For this purpose, however, it is necessary to connect the output to an oscilloscope. Figure 58 shows a typical vibration pattern obtained on the screen of an oscilloscope connected to the basic microwave instrument output. From the scope display, it is possible to determine accurately both vibration frequency and amplitude. From damping patterns, such as the pattern in Figure 58, it is possible to determine some of the elastic characteristics of the materials tested.

Other advantages of microwave vibrometers are that measurements are made without contact; therefore, without loading or otherwise disturbing the test item. The frequency range of the instrument for vibration measurements extends to several hundred megahertz, limited only by the response capability of the oscilloscope.

d. Thickness of Nonmetals. Another capability of microwave interference instruments is the ability to measure the thickness of nonmetallic materials and structures bounded by parallel surfaces. Glass fiber panels, radomes, nonmetallic walls, plates, sheets, and so on, have been gaged from a thousandth of an inch to several inches in thickness. The incident beam is reflected at both the top and bottom surfaces of the object. The two reflected beams interfere, and this interference allows gaging of the thickness of the object much as the color reflected by a soap film indicates the film thickness.

The reflectometer which was illustrated in Figure 55 can be used to create and measure the interference pattern. Thickness is plotted horizontally on the readout in units of the wavelength in the material for purposes of generality. If the wavelength is taken to be 1 inch, then the numerical designations on the horizontal axis are in inches. Meter reading (reflected amplitude) is plotted vertically.

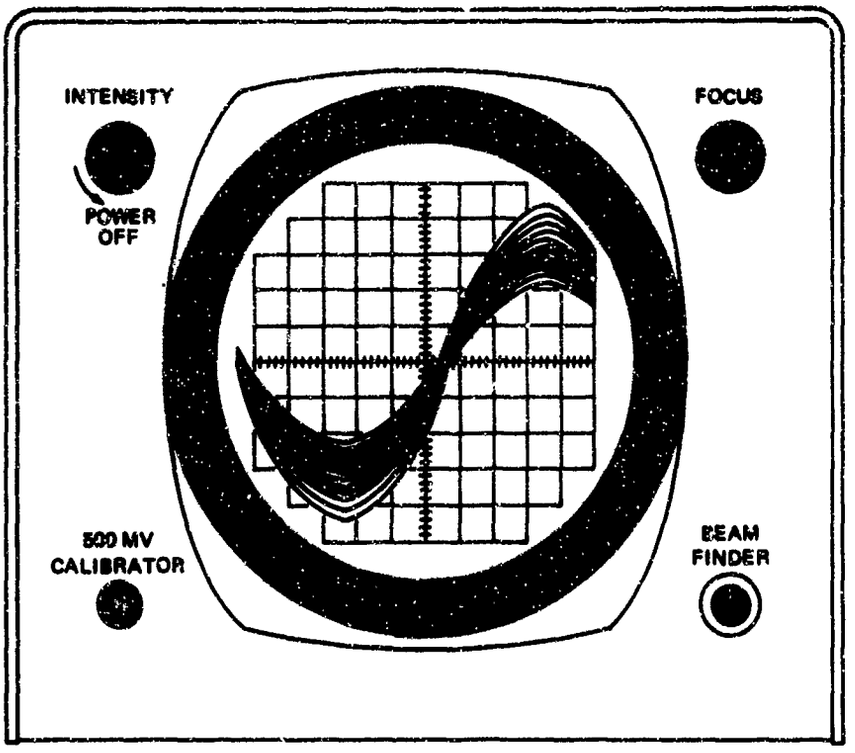


Figure 58. Oscilloscope Display of Vibration Patterns Obtained with Non-Contacting Microwave Reflectometer

Two curves are plotted, one for a material which is very absorptive to microwaves, the second for a low absorption material. In either case, maximum reflected amplitude occurs when the material thickness is an odd quarter multiple of the microwave wavelength used. Reflected amplitude is minimum for thicknesses which are even quarter multiples of a wavelength. Camera manufacturers use the same principle when they coat camera lenses with a so-called "nonreflecting" coating. Such lenses usually reflect with a faint violet color because the coating thickness is chosen to be optimum for the center wavelength of the visible light spectrum and is imperfect at the two ends of the spectrum.

e. Coatings. The thickness of coatings of one nonmetallic material over another or on a metal can often be measured in a similar manner. It has even been possible to measure coatings which are less than a thousandth of an inch thick, using the microwave reflectometer together with a special probe known as a hypodermic needle probe (shown in Figure 55). Microwaves emerge from the tip of this probe and give a spot size about .020 inch in diameter.

f. Metal Thickness. Although microwaves do not penetrate metals by more than a few millionths of an inch, they can nevertheless be used to determine metal thickness. This is done by using two reflectometers, one aimed at the top, the other at the bottom of the metal sheet, plate, ingot, or structure to be measured. Each reflectometer measures accurately the distance between itself and the nearest surface of the metal. Electronically adding these two distances, while subtracting the known distance between the two reflectometers gives the thickness of the metal object tested.

There are some substantial advantages (and at least one substantial disadvantage) to using microwaves for metal thickness measurement. For one thing, measurements are made without contact. The sensing heads can be several inches away from the object measured. The accuracy of measurement is independent of the thickness of the test item. Typically, the accuracy is ±.002 inch at 10 gigahertz (10 billion Hertz, abbreviated GHz). Thick plates, ingots, etc. can be measured with the same accuracy (±.002 inch) as thin sheets, an obvious advantage in the measurement of thick materials, although usually not satisfactory for quite thin materials. In the gaging of thick material, microwaves offer advantages over X-ray thickness gages, which are not only limited in range but become increasingly expensive for thicker material.

Since there is no penetration of the test object, the measurement is unaffected by variations in composition or properties of the material tested. There is no need to recalibrate even for such dissimilar metals as steel, aluminum, copper, and the like. Similarly, the measurement is unaffected by high temperatures; i.e., the test item can be at a high temperature when measured.

66. DETERMINING MATERIAL CHARACTERISTICS WITH MICROWAVES

a. General. Another major area of applying microwaves to NDT is to probe materials on the molecular scale. Quite a number of tests can be made, all involving dielectric measurements.

The principles underlying such tests follow from an examination of how atoms and molecules respond to microwaves passing through them.

When microwaves penetrate dielectric materials, they are influenced by only three parameters of the material: (1) the dielectric constant, (2) the loss tangent, and (3) the shape and dimensions of the material. Any material reacts to an electromagnetic and electric field because the material contains charge carriers which can be displaced. In dielectric materials, such displacement is called polarization. There are four kinds of polarization:

(1) Orientation polarization, involving the rotation of atoms or molecules into the direction of the field.

(2) Atomic polarization, involving distance changes between adjacent atoms.

(3) Electronic polarization, involving a distortion of the shape of the electron cloud around an atom.

(4) Space charge polarization, involving the movement of free charges within the material.

These four types of polarization account for the dielectric constant of a material. The dielectric constant is frequency dependent. As the frequency is increased into the radio frequency range, a point is reached where the molecules of most substances can no longer rotate fast enough to remain in phase with the applied field. Here the contribution which orientation polarization makes to the total polarization of the substance begins to decline, and with it the dielectric constant. If the frequency continues to increase, the molecular orientation effect disappears completely, leaving only the other sources of polarization. At still higher frequencies, which may range through the microwave and infrared, the dielectric constant is again relatively constant but at a lower value. Water is an exception. At microwave frequencies, its dielectric constant remains very high, which provides a basis for microwave moisture gaging.

The loss tangent, as the name implies, is a measure of energy lost in the form of heat when a dielectric substance is placed into an electromagnetic field. It is the ratio of the power dissipated to the power stored per cycle. Such heat losses are most easily attributable to friction between molecules although there are also other contributions. For example, in substances which contain free electrons, ordinary resistive losses contribute to the total loss tangent.

The loss tangent can sometimes be so high that the heat generated may be appreciable when a material is exposed to high frequency fields at substantial power levels. Such heat has been used for welding certain types of plastic, cooking meat (the familiar radar range), and drying potato chips.

Dielectric constant and loss tangent are functions of material composition, structure, homogeneity, orientation, moisture content and similar factors. This leads to a number of interesting practical applications of microwave measurements of dielectric properties such as measurements of moisture content.

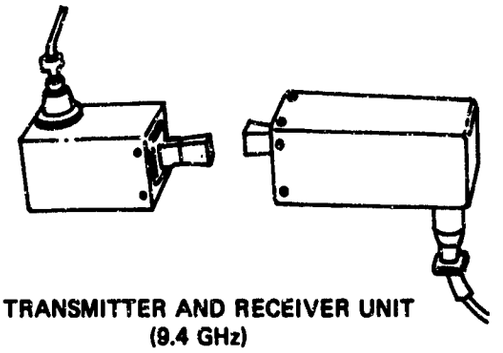
b. Moisture Gaging. At microwave frequencies, the water molecule is unique in that it has an extremely high dielectric constant and loss tangent compared to virtually all other materials in which water may be found. As a result, the water molecule is both a very good absorber and reflector of microwaves. Water will absorb several thousand times more microwave energy than a similar volume of almost any dry substance.

For this reason, microwaves can be used to monitor the moisture content of many materials almost instantaneously. This can be done continuously and directly on the production line. A typical through-transmission setup for moisture gaging is shown in Figure 59. The test item to be checked for water content is placed between a transmitter unit and a receiver unit, and

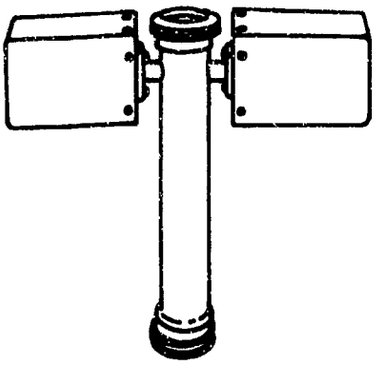
the energy transmitted through the material is measured and the presence of even a few tenths of one percent water in the material between the sensing heads may double the microwave absorption of the substance.

Microwaves have been used to test a wide variety of products for moisture content, including food products, dairy products, soap, textiles, paper, grains and other agricultural products, chemicals, ammunition, rock products, wood, ore concentrates, sand, and fertilizer. Usually, the sensing units are installed directly on the process stream (pipeline, machine, chute, belt, tank, etc.) at an appropriate point of measurement. Contact with the material being tested is not required.

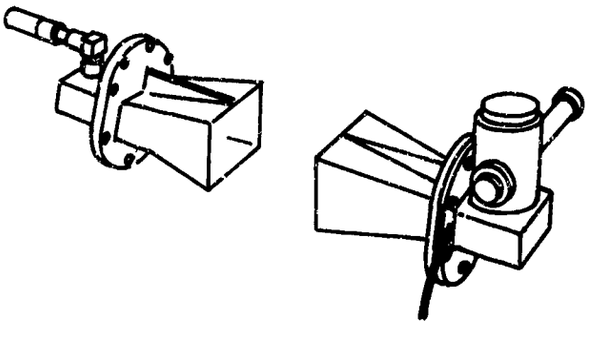
The sensing units shown in Figure 59 are useful if the material is in the form of a sheet or board and, in the case of granular materials, on conveyor belts. On the other hand, liquids, pastes, powders, slurries, and granular materials which are normally handled in pipelines during production may be measured by installing the transmission units directly on the process pipe.



TRANSMITTER AND RECEIVER UNIT
(9.4 GHz)



TRANSMITTER AND RECEIVER MOUNTED ON PROCESS PIPE FOR MEASURING PRODUCT MOISTURE



TRANSMITTER AND RECEIVER FOR TRANSMISSION MEASUREMENTS AT 2.8 GHz

Figure 59. Microwave Moisture Sensing Equipment

The standard laboratory technique of determining the moisture content of materials involves several careful weighing and drying operations. Errors can occur for a variety of reasons, such as exposure of the sample to the atmosphere, incomplete drying and driving off constituents other than water. One of the advantages of the microwave moisture gage is that measurements are made instantaneously on the material in its natural state. Since results are available immediately, corrective action is not delayed.

In continuous process measurements, results may be recorded continuously. Output terminals are provided on the rear panel of the basic instrument for this purpose. An alarm circuit may be added to alert the operator to an out-of-tolerance condition.

c. Degree of Cure. Polymerization, the cross linking of molecules into long chains of macromolecules, is accompanied by changes of dielectric constant and loss tangent. Such changes occur, for example, as resins cure or as rubber is vulcanized. Microwaves can be used to monitor these processes and indicate when cure is complete. The reflectometer head is adjusted for zero instrument reading corresponding to the uncured condition. As curing proceeds, the meter deflects and finally stabilizes as curing is completed.

d. Orientation. Sometimes it is important to know whether a material displays orientation. Microwaves are well adapted to detecting orientation. When the sensing head is rotated relative to the test object, orientation effects will show up as variations in reflected microwave power. Examples of oriented materials are wood (which shows strong orientation in the direction of the grain) and glass fiber, resin-impregnated aerospace materials. The direction of the glass fibers can be easily determined. Similarly, microwaves have been used to determine the degree of orientation of small metal wires embedded in a nonmetallic medium.

e. Equipment for Dielectric Measurements. While all the sensing units described earlier respond to variations in dielectric properties in materials, units have been designed specifically to allow direct measurements of dielectric constant and loss tangent. Each is an accessory of the system and may be interchanged with any of the other sensing units.

67. SAFETY FEATURES

Because microwaves are a harmless form of radiation at the low power levels used in NDT, the protective measures required for such other methods as X- or gamma-radiography are unnecessary with microwave NDT.

68. ADVANTAGES AND DISADVANTAGES

a. General Advantages. Microwave testing offers many potential advantages to the nondestructive testing field. Much of the equipment is modular in design, consisting of a basic analyzer and display unit to which may be connected a variety of sensing units, probes, recorders and other accessories. These are combined in different ways to serve different test purposes.

Applications of microwaves in materials testing can be divided into two areas: nondestructive testing and process instrumentation. Both areas are expected to experience considerable growth within the next few years.

b. General Disadvantages. A significant disadvantage of microwave metal thickness gages is that dynamic measurements, made, for example, on a rolling mill, usually involve a fair amount of flutter in the pass line of the material. Some flutter can be tolerated by the microwave instrument. However, if the amplitude of the vertical flutter movement exceeds about 1/4 inch, a measurement error may result. Since flutter amplitudes in many cases exceed an inch or more, the usefulness of microwave thickness gages is limited by this consideration. However, where flutter is less than 1/4 inch, good results may be expected.

c. List of Advantages.

(1) Can be used to detect flaws such as laminations or voids in nonmetallic structures and products, monitor material properties, check cure or composition, check moisture content, determine thickness, monitor vibration, etc.

(2) Has the ability to penetrate large masses of nonmetallic materials.

(3) Requires access to only one surface of the test item.

d. List of Disadvantages.

(1) No standardized procedures are available for testing, and the method is still being explored and developed.

(2) Correlation between the size of the flaw and intensity of scattered energy is difficult to perform.

(3) Extremely sensitive to position and geometry when evaluating materials properties.

Section XI. INFRARED NDT

69. BACKGROUND

Thermal inspection by the infrared (IR) method (sometimes referred to as IR thermography) is performed using a radiometer-equipped camera system to scan radiant energy patterns emitted from the surface of heated test items, and to indicate differences in these patterns caused by flaws. This method of NDT is also in the developmental stage and is not as well established as others such as ultrasonics and radiography. This method of testing is a relatively recent addition to the NDT field, although it has long been used

for applications such as IR aerial photography. The method offers ... for testing of such items as filament wound rocket engine cases and ... boards. It has been suggested as a method of testing the surface of a ... vehicle in an environmental test chamber to monitor heat variations in the structure.

This type of testing encompasses an area of the electromagnetic spectrum between the areas occupied by microwaves and visible light; i.e., wavelengths extending from the red end of the visible spectrum at 0.7 microns to the beginning of microwaves at frequencies of 10^{12} to 10^{15} Hertz. The method is based on the principle that every object emits heat at various intensities and wavelengths depending on the physical characteristics of the object. In this type of testing, a test item may be heated so that the test item emits infrared radiation. Residual processing heat may also be used – as can the heat generated by the test item itself (such as a circuit board defect). The intensity and wavelengths of these radiations depend on the temperature, structure, and composition of the material. The detector system used is sensitive to radiation in the infrared range. Scanning and temperature sensing are performed using a sensing system (camera) that does not come in contact with the test item surface. The surface is therefore not disturbed or modified in any way. The detector (radiometer) system produces voltages that can be amplified and displayed on meters, C-scan recorders, strip chart recorders, oscilloscopes, or self-contained-developer film.

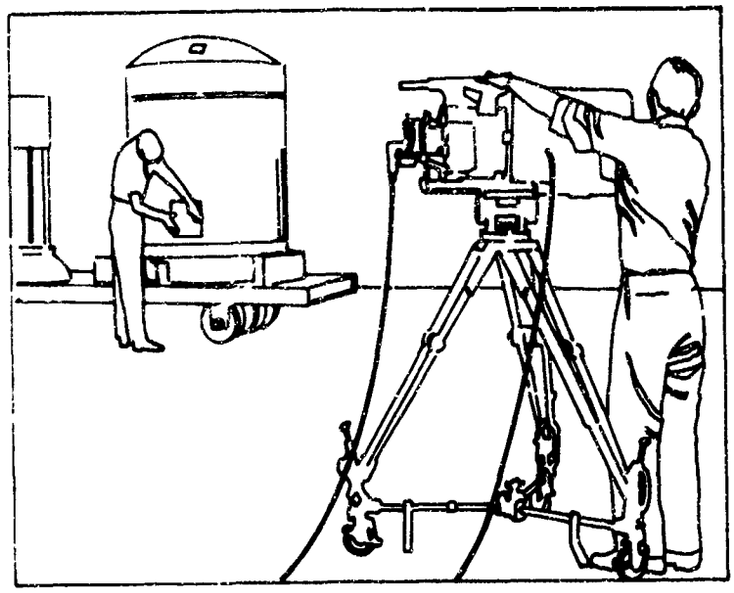
One infrared scanning system makes heat patterns instantly visible on a 5-inch TV-like cathode ray tube. Applications suggested for such instruments have included insulation leaks, hydraulic leaks, heat from friction, faulty bonds, defective laminations, clogged pipes, defective deicing systems on aircraft windshields, and so forth. Thermal scanning techniques allow immediate observation of changing heat patterns in stationary test items, as well as infrared images of moving objects.

Examples of applications for thermal testing include inspection of many types of laminated structures (including honeycomb types). In solid materials, flaws in welds can often be detected. If there is symmetry in the test item and if a favorable balance of radiant energy is conducted to the heated test item's surface, then the item is a good candidate for thermal (IR) testing. Thermal patterns can then be developed and testing will reveal the internal structure of the item.

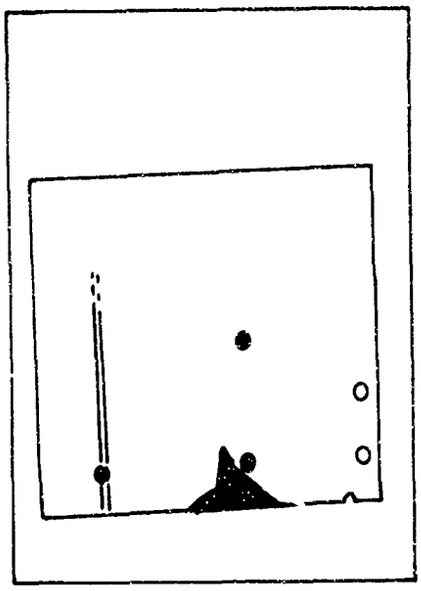
70. EQUIPMENT

Equipment in this field is being rapidly developed. Tripod cameras containing IR detectors (radiometers), or infrared detector and amplifier, are often used. (See Figure 60.)

The camera scanning system typically is equipped with an auxiliary readout or display system. A collecting mirror focuses radiation onto the infrared detector which generates an electrical signal exactly proportional to the incident radiant flux. The signal received is amplified and serves to



ROCKET MOTOR COOLING
AFTER ITS REMOVAL FROM 110° F OVEN IS READY FOR IR
THERMOGRAPH CAMERA



DEFECT IS SHOWN BY DARK
SHADOW IN LOWER PART OF PICTURE.
BLACK SPOTS ARE SILVERY
THERMOCOUPLE PADS

Figure 60. Tripod Mounted Camera and IR Thermography Equipment Setup

modulate the brightness of a glow modulator lamp (which can be focused onto a self-contained-developer type film). The position of the lamp image on the film is controlled by the motion of the scanning mirror. This results in a recorded thermal pattern having one to one correspondence with the infrared scanning pattern.

In addition to the film type recording technique, the thermal testing system may also display the thermal pattern on a cathode ray tube or storage (memory) tube display.

The typical camera used in infrared nondestructive testing may have a field of view of from 10 to 20 degrees, a spot size of one milliradian, and a thermal sensitivity in the approximate range of 0.1 degree centigrade.

71. EXAMPLE OF THERMAL TESTING APPLICATION

In testing a filament-wound rocket motor case, the following general procedure is used. The entire rocket motor case is carried into a warming room and heated to a few degrees above ambient temperature. On removal from the heating room, the case immediately begins to cool. The cooling process takes

place by both radiation and convection from the test item surface. Thus, the heat stored in the interior of the rocket motor case is continuously flowing outward. In a cylindrical rocket motor case, the flow of heat is generally symmetrical. If there is any lack of uniformity in this symmetrical pattern, the flow pattern correspondingly reflects the flow impedance in the area of the flaw. The flow of heat may be impeded, for example, if there is a lack of bond at any point. In the surface region above the lack of bond, a cool spot will result and show up on the display device.

In IR thermography, there is practically no limit to the size of the object that can be tested, since the camera need only be moved farther away from the test item. It is not necessary to use a film the same size as the test item — as is required by radiography. When the camera is moved farther away from the test item, a loss in resolution results. However, when a flaw area is observed from a distance, it can readily be examined in detail with high resolution by bringing the camera close to the flaw.

72. INTERPRETATION OF INDICATIONS

In general, thermal testing or IR thermography fills many gaps in the current art of NDT. It may be applied as an independent technique; it may be used to supplement other methods; or it may be used to locate flaws for further examination by other methods.

Infrared has proven to be particularly valuable in macro and micro electronic circuitry to find many defects and incipient failure points where, for example, a poor weld or bond will cause a higher resistance and a resulting higher temperature which can be readily identified.

73. USE AND CALIBRATION OF RADIOMETERS

Radiometers should be calibrated so that the results obtained from test item emissions can be presented in absolute units independent of the type of instrument used. It is therefore necessary to obtain the detector response to a known quantity of radiation. Calibration procedures are discussed in the literature. Calibration would not be required when only comparative indications are required, such as in the examination of an insulated tank when an area of different temperature would indicate a void in the insulation.

74. ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Thermal inspection can be used at relatively low cost for large test items to indicate thermal gradients which indicate flaws, overheating of electronic components, poor bonding of coatings, or porosity in castings.

(2) Many infrared and thermal tests produce permanent records.

(3) Many infrared tests are adaptable to automatic control.

b. Disadvantages.

(1) Surface conditions may influence the radiation emitted from the test object.

(2) Uniform and proper heating of the test object is sometimes difficult.

(3) Positioning of the heat source, test item, and detector may be critical.

75. SAFETY FACTORS

Since thermal testing uses no high energy radiation, it is not hazardous to personnel or to sensitive devices such as semiconductors.

Section XII. LIQUID CRYSTAL NDT

76. BACKGROUND

Liquid crystals are being used as a relatively new NDT method and are still under development. Some of their unique properties that make them promising for use in NDT are discussed here.

Since the liquid crystals used in nondestructive testing are generally derivatives of cholesterol, particularly the esters, the designation cholesteric has been given to the entire class. Pure cholesterol does not behave as a liquid crystal; it is the derivatives, such as the cholesteric esters, which possess the unique optical characteristics which make them useful in NDT.

Liquid crystals are commonly designated in three classes: smetic, nematic, and cholesteric. In the smectic class, molecules are oriented parallel to each other in well-defined planes, somewhat similar to layers of honeycomb.

In the nematic configuration, the molecules are still parallel to each other but do not exhibit planar cohesion as do the smectic crystals. The cholesteric state (which is of significance in NDT) is similar to the nematic in that the molecules are almost parallel to each other, but they are subject to slight helical displacement. An idea of their structure may be obtained by visualizing cards in a stack, each with one corner bent up. The cards lie flat except for their bent corners, which cause a slight twist in the overall configuration. These crystals not only undergo changes in their liquid structure in response to changes in temperature but they exhibit a unique optical characteristic of selectively scattering incident white light also in relation to temperature variations.

Although these crystals were discovered years ago (c. 1888 by Reinitzer), they were studied almost exclusively by organic chemists until recently. Their development owes much to J. L. Fergason who published articles on these crystals in Scientific American, Volume 211, No. 77, in 1964 and later in other magazines and reports.

Some of the optical characteristics of the molecular order of cholesteric crystals include the following:

(1) Birefringence. This is the characteristic of transmitting light waves at different velocities in different directions through material. All liquid crystals exhibit this phenomenon.

(2) Optical Rotation. Optical rotation of polarized light is shown only by the cholesteric state. Cholesteric crystals are in this respect the most optically active substances known, since they rotate light through an angle several hundred times that of the usual optically active materials.

(3) Scattering of White Light. The scattering of white light reflects different wavelengths, giving iridescent colors. Colors observed are a function of the specific cholesteric substance, the angle of reflected and incident radiation, and the temperature.

These characteristics are responsible for the utilization of cholesteric crystals in nondestructive testing. These materials are generally colorless on each side of the liquid crystal state – colorless, that is, in the true solid and the ultimate true liquid phase. Each cholesteric liquid crystal responds in its own way to changes in temperature. The change may be only from red to green, or from red through the entire color spectrum, or from green to blue. The important characteristic to remember is that each color corresponds to an exact temperature of the material being tested.

Since liquid crystals have the ability to reflect colors dependent upon the temperature of their environment, they may be used to project a visual, color picture of the transient temperature anomalies, or minute thermal gradients associated with material flaws. These flaws may be unbonded areas, cracks, etc., which impede a flow of heat sufficiently to disturb the normal temperature patterns of a material being tested. The flaws will then show up as distinct color patterns, because of their impaired thermal transmission characteristics.

Since iridescent colors of liquid crystals arise from light reflectance, it is necessary (to allow most effective observation) to paint or spray liquid crystals on a dark background, previously prepared from practically any water-soluble black paint.

77. USE OF LIQUID CRYSTALS IN NDT

a. Thermal Definition of Cracks. Liquid crystals can be used successfully to detect cracks in copper, aluminum, and titanium test items. The

liquid crystals are painted on the surface of the test item in a thin film. Heat is injected by a point source moving at a constant speed over the surface of the test item. (See Figure 61.) The temperature at a point that is fixed relative to the moving source remains constant if the thermal properties of the test item surface are constant. If the material contains a flaw, however, the temperature pattern surrounding the heat source is perturbed. The presence of a crack alters the rate at which heat flows through the material. Surfaces of approximately 0.040-inch thick plates of copper, aluminum, and titanium can be successfully tested in this manner. Welds in steel approximately 3/4-inch thick have also been satisfactorily tested with liquid crystals.

b. Leak Detection. It is possible to alter the thermal response of a cholesteric mesophase by adding various contaminants. Thus, a given color will be produced in response to a given temperature depending on the nature and concentration of impurities. This principle can be used in leak testing in that impurities such as small amounts of gaseous contaminants change the color of a given liquid crystal coating and therefore pinpoint the location of small leaks in a pressure vessel. For example, the vacuum tightness of

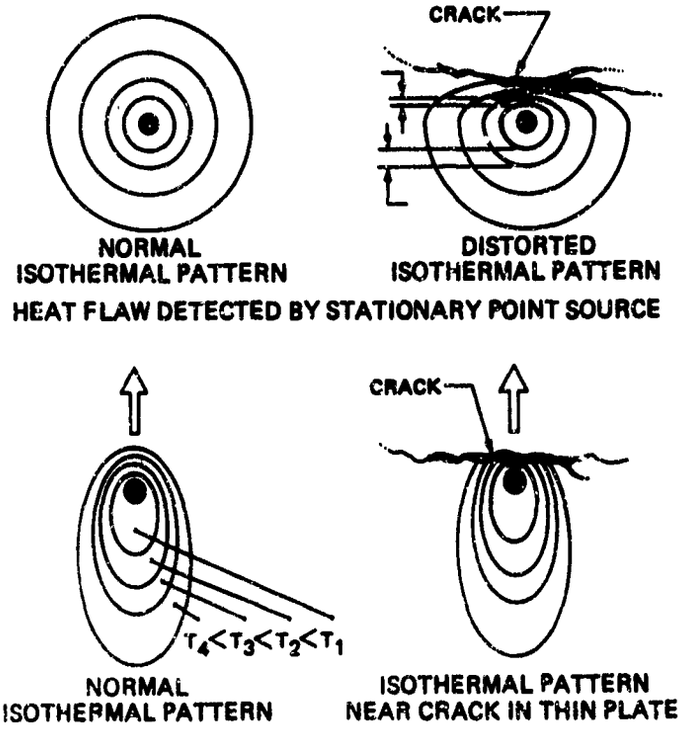


Figure 61. Isothermal Pattern Around a Moving Point Heat Source

a container fabricated with roll seam welds can be tested for weld integrity by first coating the container with a selected liquid crystal material, and then pressurizing it to about 5 psi with a contaminant gas such as acetone; any gas escaping through small leaks in the weld seam will cause a change in the transition temperature of the coating (a color change) at the site of the leak, thus allowing exact location of any weld flaws. It should be noted that these indications do not provide quantitative information relative to, for example, leak rate. Liquid crystals have also been suggested (and preliminary tests conducted) as a check on items that have been tested with penetrants.

Liquid crystals may be applied to the questionable area to detect the presence of contaminating penetrant residue within crack areas which are not entirely detectable in the usual manner; i.e., they are not visible over the full extent of their length with normal penetrant development. This use of liquid crystals over areas where penetrants have been applied helps bring out formerly hidden areas of the crack and can be used to detect fatigue cracks and flaws in welds. The liquid crystals are painted over the questionable area in a thin film. The area is then warmed to the transition temperature range. The contaminants and the flaw are clearly revealed by color transitions.

The testing performed to date indicates that when cleaning and thorough drying of weldments in preparation for penetrant inspection is a problem (because of large bulk or adverse field conditions) liquid crystals may be used for such testing as well as to perform a confidence check on liquid penetrant testing effectiveness.

c. Bond Inspection and Other Tests. Liquid crystals may be used to inspect brazed or adhesive bonded structures (such as those used for advanced aircraft and liquid missile tubing). As in many other thermal tests for bond inspection, the surface temperature is monitored while the panels are cyclically heated and cooled. An attractive feature of liquid crystals in this application is that they can be directly observed to detect anomalies related to variations or flaws in the bonded structure. Many of the titanium composites and those of heat resisting metals currently under development are well suited to thermal testing with liquid crystals. Comparable structures fabricated from aluminum are not as easily tested with liquid crystals because of the rapidity with which small gradients on the surface are dissipated by lateral heat flow in the face sheet.

For some applications of this method, photoflood lamps, controlled by transformers, are used to heat the test surface. Various other techniques are used to obtain a suitable thermal gradient for test purposes, depending on the size and nature of the test item.

78. CONCLUSIONS

The liquid crystal NDT method is a new and rapidly developing field. Its advantages include simplicity and visually observable indications. Its uses

and applications have not as yet been thoroughly explored. Liquid crystals provide a quick and convenient means for direct observations (in high ambient light environments) of small thermal gradients near room temperatures. They are capable of detecting a broad range of temperatures. In addition to the tests described in this section, liquid crystals are being evaluated to test the uniformity of various coatings. Liquid crystals are also available in encapsulated form which has advantages for some types of testing, although this adds to their expense.

79. ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Direct observation is used.

(2) Temperature can be rather precisely correlated with color changes.

(3) Large parts or small areas (such as leak areas) can be tested.

b. Disadvantages.

(1) Since this method of testing is relatively new, procedures have not been standardized.

(2) Flaw depth is not indicated.

(3) Special surface preparation is required.

(4) Removal is difficult.

(5) Electronic circuits may be shorted or contaminated.

(6) Color discrimination varies among inspectors.

(7) Color displays are frequently transitory.

Section XIII. KRYPTONATION NDT

80. BACKGROUND

a. General. Krypton-85, an inert gas radioisotope, is another method being developed for use in NDT applications. Krypton-85 can be incorporated into the matrix of practically any solid material to make the material radioactive and usable for nondestructive tests. The Krypton can be incorporated into a material by ion bombardment or by gas diffusion. It remains in the immediate surface layers of the test item, concentrated in the first 1 to

10 microns. As temperature, oxidation, or corrosion affect the test item surface, measurable amounts of trapped beta-emitting Krypton-85 are released. The radiation released forms the basis for a precise measurement of: (1) the peak surface temperature the test item has reached; (2) the amount of oxidation; (3) surface wear; or (4) corrosion. Since these effects are observed by monitoring the rate of release of gaseous Krypton-85, there is no need for radio-chemical analysis of the test item, which often calls for destructive wet chemical analysis.

b. Historical Development. Early observations by L. B. Loeb published in his book entitled Processes of Electrical Discharge in Gases, Wiley, New York, 1939, described the trapping of inert gases in solids following ion bombardment under the influence of a potential oltage drop. This early work dealt with gas discharge lamps. Later experiments indicated that the gas atom is trapped interstitially between the planes of the solid crystals. However, due to internal strains, the gas atoms will actually take a substantial position in the crystal lattice by forcing off some of the metal atoms. The effects are still being investigated. Later techniques for kryptonation includes using a closed-off pressure bomb in which the test item is placed while gaseous radioactive Krypton-85 is introduced at low temperature and pressure.

81. TECHNIQUES FOR KRYPTONATION OF TEST ITEMS

a. Diffusion. In incorporating Krypton-85 into a solid, the gaseous Krypton-85 is introduced at low temperature and pressure into a "bomb" which is closed off, and the temperature is raised by oil bath heating or by use of a furnace. (See Figure 62.) The pressure is controlled by a combination of the volume of gas introduced into the bomb plus temperature increase. A pressure gage is connected directly to the bomb. Temperature measurements may be based on oil bath temperatures or may be calculated from the measured pressures. At the completion of a run, the material is quenched by immersing the pressure bomb in liquid nitrogen, and the kryptonated item is removed. The various tests previously described can then be performed on the item and their effects precisely measured.

b. Ionization. Early work in incorporating Krypton-85 into such targets as aluminum, copper, gold, and silver used the ion bombardment technique. The apparatus required for this technique is shown in Figure 63.

c. Measuring Apparatus. The radioactivity of the kryptonated test items can be determined as the measure of the quantity of gas collected. All the activity measurements can be made with a Geiger tube and scaler.

d. Diffusion of Solids. Over 50 different solids have been "kryptonated" by diffusion at high temperature and pressure. These include elements, inorganic compounds, alloys, glasses, rubbers, plastics and proteins. No solid yet investigated has failed to collect Krypton-85 and to retain some fraction of this collected gas with time at room temperature.

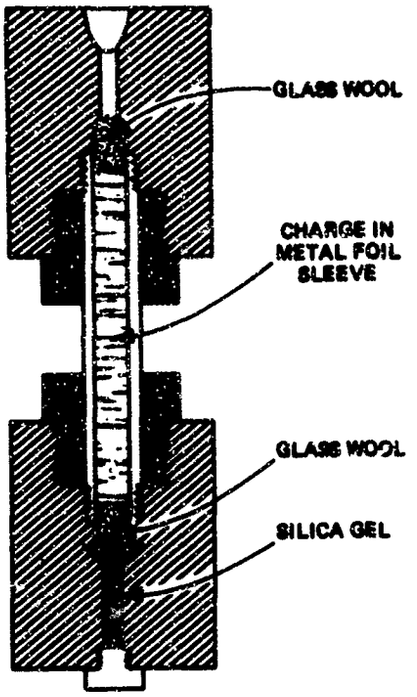


Figure 62. Kryptonation Apparatus (Pressure Bomb)

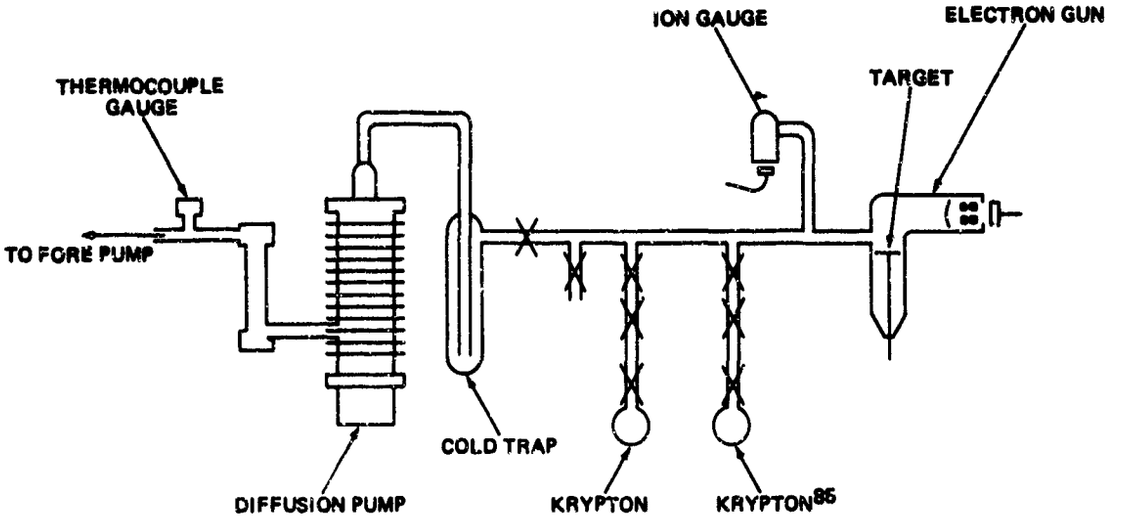


Figure 63. Kryptonation Apparatus for Ion Bombardment

82. SAFETY

The kryptonates are relatively safe forms of radioactivity, although some kryptonated solids may be soluble in some reagent and may release the contained Kr^{85} to diffuse through the atmosphere. Even if accidentally inhaled, the Kr^{85} is incapable of being metabolized or absorbed by the body. Its beta-decay daughter is stable, so there is only the radiation from krypton. By confining the Kr^{85} to a near-surface zone (as is done in NDT), a high specific activity can be attained with the safety of low total activity.

83. POSSIBILITIES FOR KRYPTONATED TEST ITEMS

Incorporation of Kr^{85} into all types of solids introduces a universal tracer. Since krypton is released from these kryptonated test items during chemical reaction or physical removal of surface, there can be widespread application in corrosion and wear studies. In addition, many applications formerly impracticable for lack of a specific isotope are now quite feasible. Besides extending and improving existing radioisotope techniques, the kryptonates offer some unique applications.

For example, the temperature-dependent loss of Kr^{85} from solid sources offers a unique way of measuring the maximum temperature attained at a surface. The loss of gas from a surface is dependent only on surface temperature (not on the bulk of the solid).

It is probably in the area of friction and wear studies that the kryptonates will provide the greatest advances. When these sources are employed in ways similar to those of other isotope techniques, a higher specific activity can be induced at the surface of interest. In addition, the escaping krypton can be collected in the gas phase (perhaps of an engine exhaust) to monitor wear. Detailed techniques and information on the various applications are increasingly available in the literature, and new developments are constantly being added to the state-of-the-art. Only a general coverage is provided here. It should be remembered that this is a relatively new method of NDT and that techniques of use are still in the developmental stage. Additional information on this NDT method can be obtained from the literature.

84. CURRENT REPORTED APPLICATIONS OF KRYPTONATION

a. General. Krypton has a half life of 10.8 years and a beta radiation strong enough for most measurements. (Half life, as previously defined, being the time required for the intensity of a radioisotope to be reduced to one-half of its original value.) A technique which has been reported in routine use in several aircraft companies permits determination of the maximum in-service temperature and the temperature distribution of turbine blades using kryptonation. It also allows obtaining an accurate measurement of wear on bearings and similar hidden components.

Although on-stream temperature measurement may eventually be possible, kryptonates now tell the temperature story after it happened. An advantage of

kryptonation is that no thermocouples, optical pyrometers or other devices are required. Thus, kryptonated test items can be used in formerly inaccessible locations.

b. Determining Unknown Temperature. For determination of an unknown temperature, the technique includes making a kryptonate of the part and putting the kryptonated part in service. As it heats, the part loses some of its krypton. At the highest temperature, it stabilizes.

Once a kryptonate is stabilized, it retains its krypton content indefinitely unless subjected to such external stresses as temperatures above the point of stability, oxidation, corrosion, or surface wear. This unusual behavior of kryptonates is the reason for their value in nondestructive testing. To check the temperature a part has reached in service (even if oxidation or corrosion has occurred) all that is needed is to reheat it in stages in a controlled chamber. The kryptonate will begin to give off radiation only after it reaches a point above the previous high temperature.

c. Testing Oxidation. Surface oxides on rubbing surfaces of a kryptonated test item influence the frictional process. A reduction or an increase in wear of the test item can occur as a result of the oxide, depending on the nature of the oxide or the thickness of the oxide layer.

Kryptonated test items lose activity from the surface if a chemical reaction destroys the lattice structure of the solid. Thus, if a corrosive film forms during the wearing process, the rate of formation of the film can be determined by measuring the loss of the Krypton-85. Unlike temperature, which must be determined after it has happened, oxide formation can be measured in kryptonated test items as it occurs.

d. Testing Wear Rates. Unlike standard methods of wear determination, the kryptonate technique permits following the wearing process during actual mechanical operation.

Again, the part can be heated to stabilize it thermally. If it can be viewed at any time during operation, direct source counting can be used to follow the wearing process. Otherwise, the effluent activity released by the part shows the wear as it occurs.

In experiments, a stainless steel cylinder has been rolled over a kryptonated copper block to test the wear caused by sliding friction. During the experiment, the block was continuously monitored with a Geiger counter.

Other experiments have demonstrated the ability of the technique to indicate wear irregularities or the sudden onset of severe wear caused by lubricant breakdown or sudden load increases. Since the technique is relatively new, calibration and standardization of results are still under development.

85. ADVANTAGES

a. Allows monitoring effects on the surface of a solid — temperature, friction, oxidation, or corrosion just by measuring the rate of release of Krypton-85.

b. Allows checking the effects just mentioned when the part is in actual service environment and is located in a place where NDT would not be possible without kryptonation.

86. DISADVANTAGES

a. Is a new technique and is still under development.

b. Involves radioactivity (but it is one of the safest radionuclides to handle since Krypton is one of the inert gases, undergoes no chemical reactions, is biologically inert, and — as a gas — diffuses rapidly to the atmosphere).

Section XIV. CORONA DISCHARGE NDT

87. BACKGROUND

a. Principles. Corona is the term given to the discharge resulting from the ionization of gases acting as a conductor between two bodies when the applied voltage exceeds a certain value but is not sufficient to cause sparking and an electrically detectable field of intensified ionization is created. The basic operating principle of the corona testing method is relatively simple; i.e., if an electric field of sufficient intensity is imposed across a void in an otherwise homogeneous dielectric material, ionization of the gas in the void occurs and electrons are accelerated to the wall of the void. The void can be detected either by the resulting minute pulse of current in the secondary of a transformer, or by the electromagnetic spectrum radiated during the collision of electrons with the wall. This principle has been used for a relatively long time to test electrical insulation but more recently has been utilized as a nondestructive test method which is still under development. ASTM Specification D-1868 covers a Method for Corona Measurement. Corona NDT equipment is commercially available.

For small test items, the surface may be scanned by use of a test probe that is polished and rounded on the end (with the test item placed under transformer oil and on a stainless steel plate for ground). (See Figure 64.) For high-speed testing on large parts, high voltage may be applied through oil-filled elastomeric wheels for both electrodes. Suitable mechanical equipment is required for handling the part and supporting the electrodes. The required high voltage may be generated by suitable transformers and associated electronic controls necessary to vary the voltage within required limits. A flaw can be detected either by the resulting minute pulse of current in the secondary transformer or by the electromagnetic spectrum radiated

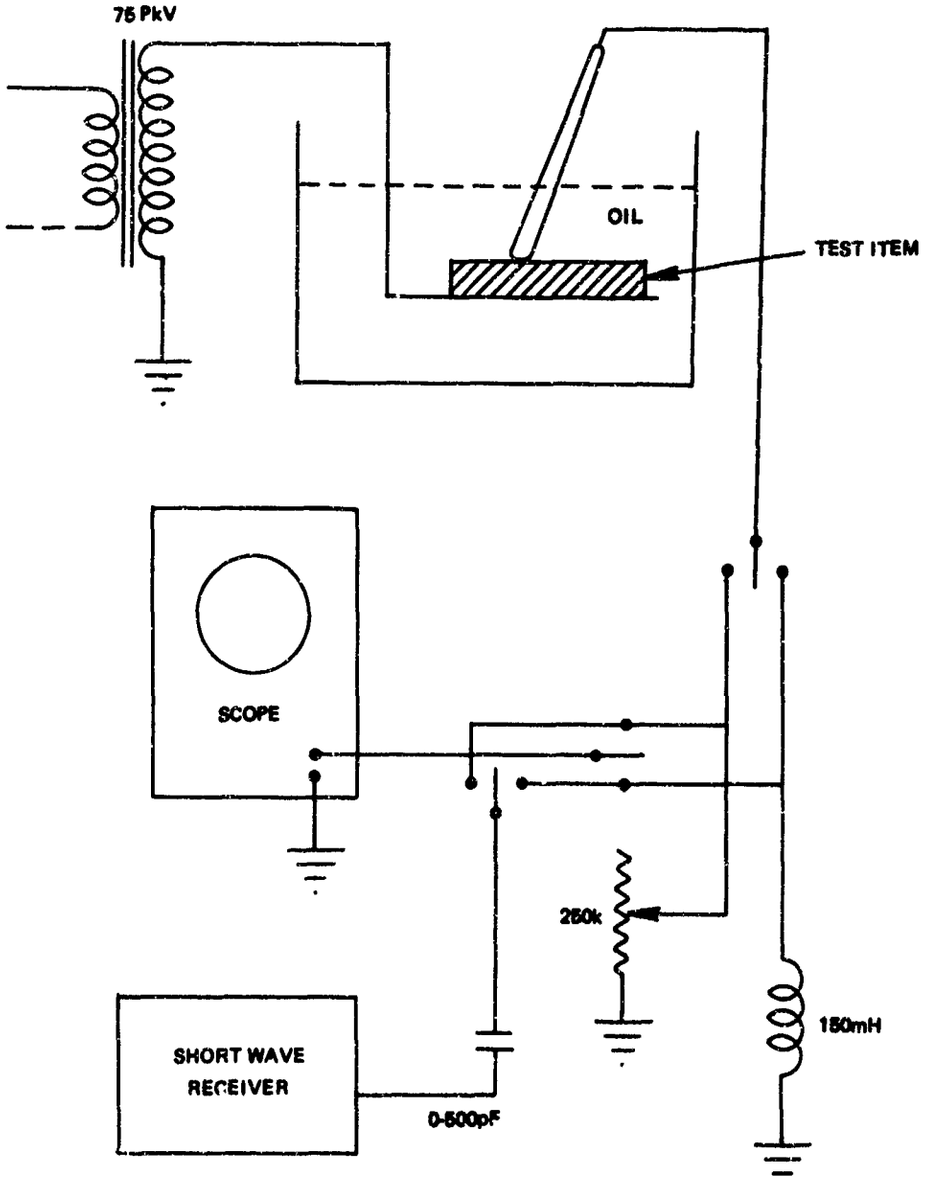


Figure 64. Block Diagram of a Corona Test Set

during the collision of the electrons with the void or lamination wall. Electronic filtering and amplifying circuits may be used to eliminate background noise and amplify the signal. Readout may be made on a strip chart recorder or on an oscilloscope.

b. History. There is a relatively long history of effort in the area of corona detection in high voltage insulating systems. Most of the early work was concerned with the testing of electrical wiring. More recently, however, the method has been used in applications such as finding voids in filament wound rocket engine cases and areas of unbond in various laminated structures.

The gases trapped in voids detectable by corona NDT may be the vapors of the solvents or residue from the fabrication process, or may simply be entrapped air. When an electrical field is established across any such gas, it obeys Paschen's law that if the field is raised high enough, ionization of the individual gas molecules will be achieved and a spark discharge will be produced. The fact that this gas may be enclosed within a solid dielectric does not affect the validity of this principle.

In general, the sparking and so-called corona potential of an enclosed gas pocket is the same as that formed between sparking electrodes. As might be expected, the duration of such a discharge is a function of the electrical circuit, the dimensions of the void and the density of the gas and, in general, is of the order of 10^{-8} - 10^{-6} seconds. Since there is no basic difference between a spark in open air and one in a void in a dielectric, the physical phenomenon of the production of electromagnetic waves occurs (as originally demonstrated by Hertz) and radio waves covering a wide spectrum of frequencies may be produced.

c. Early Detection Methods. One of the earliest corona detection methods was based on the production of ozone from the entrapped air. The absorption of ozone by the insulation materials was measured by a differential pressure method employing a manometer. Such a method would be of particular interest for electrical insulation measurements not only because of the direct relationship between the quantity of ozone produced and the amount of ionization, but also because of the known deleterious effect of ozone on insulating materials. Another interesting means for the detection of corona was the use of an ultrasonic transducer in an oil-filled insulating system for the detection of the noise produced in connection with the spark discharge; this method, however, suffers from the interference of magnetostriction noises. Another use of the generation of noise by sparking as a means for corona detection — and probably the earliest of all — was the use of a microphone under oil for the detection of audible discharges.

Another simple detection means was the use of a neon bulb across the impedance coil of the ground circuit of the high voltage system for the visual observation of light flashes of the voltage generated across the coil during corona discharges.

In recent years, most of the engineering efforts directed toward the discovery of corona discharges in high voltage insulation systems have relied upon the voltage difference generated across an impedance coil and have been observed either with a vacuum tube voltmeter or on an oscilloscope. Attempts have been made in recent years to make the latter method quantitative by calibrating the instrumentation through discharges of known energy generated in test sets.

88. EQUIPMENT

a. Typical Equipment. Typical, commercially available corona detection equipment is described in the following paragraphs. (See Figure 65.)

b. The Corona Test Set. With a typical corona test set, high voltage is applied to the test item (as in a regular high voltage breakdown or dielectric strength test) through a suitable probe with the test item immersed in oil. Any corona generated within the item travels back to the test set superimposed on the high voltage wave. Since corona frequencies are much higher than the applied high voltage frequency, they may be separated from the high voltage with a properly designed filter. This high pass filter or "pickup network" offers a low impedance path to the low amplitude corona signal while blocking off the high voltage. From the corona pickup network, the signal is fed to appropriate equipment known as the "corona detector" which displays the corona pulses on an oscilloscope so that magnitude, repetition rate, and other details may be observed. The detector may also include calibration equipment for measuring the relative magnitude of the corona.

A great deal of attention has been given to the design of corona NDT ground probes with respect to the electrode shape in contact with the work. A flat probe gave trouble with early ionization at the sharp edges, as did a pointed probe. It has been reported that a probe shape which produces good results is a hemispherical-tipped 5/16-inch diameter brass rod. In practice, the avoidance of surface arcing can be a problem since this produces serious interference with the subsurface signals. It is possible, however, for an experienced operator to discriminate between such signals. According to recent literature, there seems to be merit in the use of a conductive rubber shoe over the metallic probe to provide the actual contact electrode. A shoe approximately 1-inch square in area and 1/4-inch radii does not reduce the subsurface corona intensity to any appreciable degree and is effective in the reduction of surface arcing.

c. Corona-Free High Voltage Supply. The corona-free test set provides an adjustable, metered, output voltage and has the necessary operating controls and safety features to perform a high voltage test. A corona-free unit is usually larger and heavier than the standard unit because more generous spacing of internal components is necessary. All high voltage connections, components, and clearances are specifically designed to maintain absolutely corona-free operation to the full nameplate voltage. Units rated above 10,000 volts usually have the high voltage section in an oil filled tank. Lower voltage units may have components encapsulated, or are otherwise designed to insure corona-free operation.

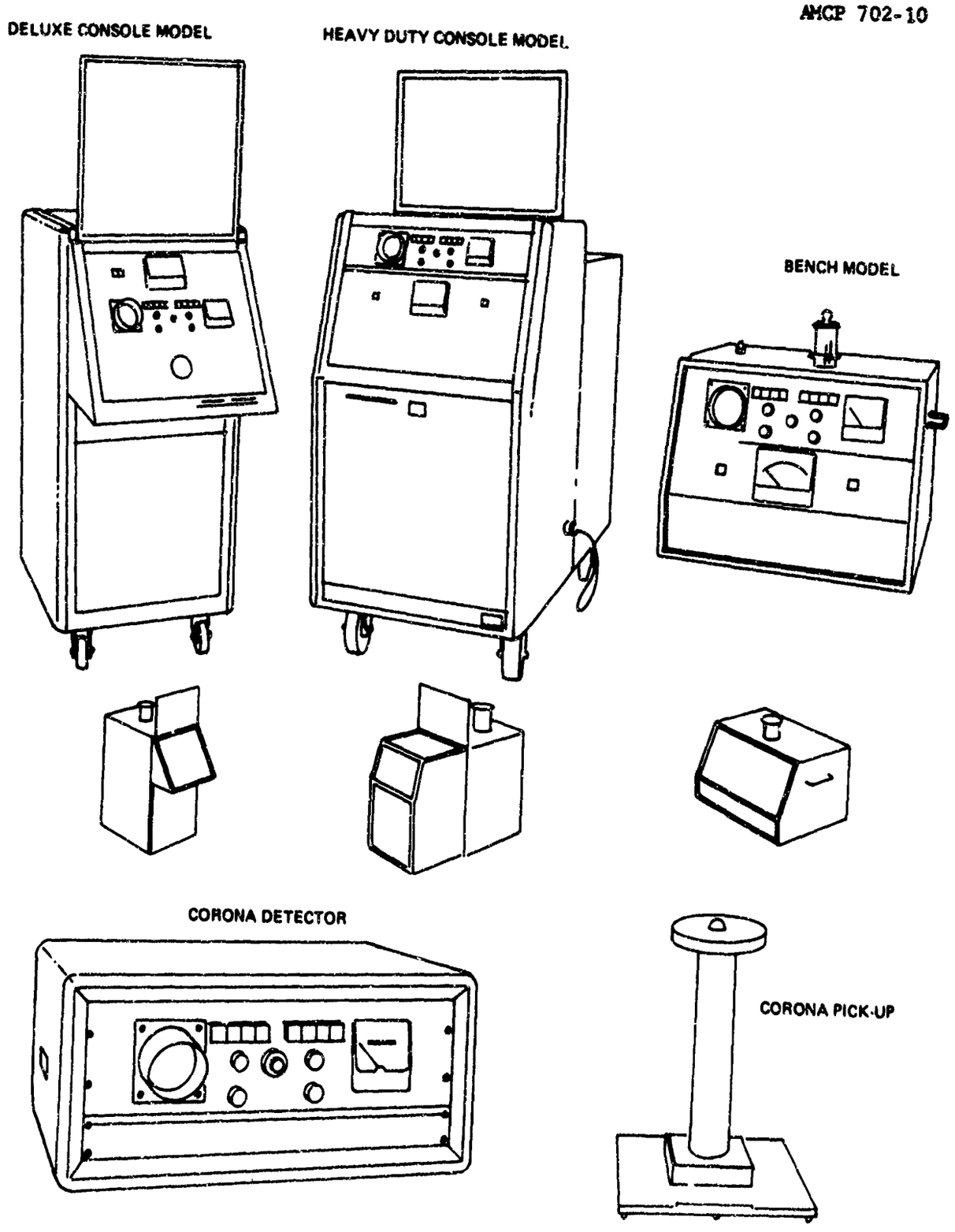


Figure 65. Examples of Various Items of Corona Equipment and Displays

d. Corona Pickup Network . The corona pickup network is a corona-free high voltage, high pass filter. Like any typical high pass filter, it consists of a capacitor in series with an inductance. The capacitor blocks off the test voltage but offers a low impedance to the high frequency corona signal. The inductance bypasses any test voltage that gets through the capacitor but offers a high impedance to the corona signal. The output terminals are connected across the inductance and feed the corona signal to the detector.

The capacitor is usually insulated and oil filled so that it can withstand high voltages without being a corona source. The inductance has the necessary shunting protective networks to prevent a voltage buildup in case of accidental open circuiting. The filter cutoff frequency is high enough to eliminate most of the test voltage and much of the stray pickup, while still being low enough to insure that none of the corona signal is lost. A measure of the high quality of the pickup is its ability to separate the low corona signal (which may range from a few millivolts to a volt or two) from the high voltage supply (tens of thousands of volts).

e. Corona Display. The corona display may be a high gain amplifier/oscilloscope provided with specialized characteristics to emphasize the corona signal while minimizing stray pickup and interference. The oscilloscope presentation differs somewhat from that of the standard oscilloscope. It is designed for the specific purpose of facilitating the determination of the presence or absence of corona, and interpretation of the type or source of corona, the magnitude, phase, and even the polarity of the corona.

To display low-level corona signals properly (when maximum sensitivity is necessary), it is essential that all extraneous signals be minimized; line noise, stray pickup, radiation, etc., all tend to mask corona signals. A heavy duty line filter can help minimize the noise picked up through power circuits, and a noise filter in the test set high voltage output circuit is desirable.

The corona signal received from the pickup network is amplified, and then is displayed on the high intensity oscilloscope tube. A dual sweep circuit is provided: the straight line (or linear) display being used when comparing magnitudes of corona pulses; the open elliptical sweep is used to show the overall corona picture. The sweep circuit of the oscilloscope is synchronized with the test voltage (and the high voltage) so that the corona pulses and the high voltage test potential are in the proper phase relationship during the display. This makes it possible to determine at what portion of the high voltage cycle the corona occurs. A four step attenuator switch and adjustable gain control permits display of corona pulses with a very wide range of magnitude.

f. Corona Calibrator. Often it is necessary or desirable to make quantitative measurements of corona. To facilitate this measurement, the corona detector may be furnished with a built-in calibrator so that the numerical value of the magnitude of corona (in picocoulombs) is obtainable. The calibrator injects a fast rise time pulse into the input of the detector

where it is amplified and displayed on the oscilloscope in the same manner as a corona pulse. It is permanently connected in the circuit and the calibration signal may be injected whenever desired without making any additional or external connections. The magnitude of the calibration signal is indicated by a wide view meter and a four position range switch. When the calibration control is adjusted so that the amplitude of the calibration spike is equal in height to the corona pulses, the corona charge can then be read in picocoulombs from the calibrator setting. The calibrator may also be used to set the sensitivity of the detector to a specified value of picocoulombs per inch.

g. General Notes On Equipment Use. Any corona in the system, whether generated in the item under test or generated within the set itself, will be displayed. It is therefore essential that the corona test set, the interconnecting cables, and everything but the item under test be completely corona-free so that any corona indications displayed will be only those emanating from the test item. The pieces of equipment forming a corona test can be obtained commercially in three separate packages or may be purchased in a single cabinet as an "integrated corona test set."

The separate units have the advantage of portability and flexibility. The test set may be used alone for normal high voltage testing, or the three units may be connected together to do corona testing.

The integrated corona test set has the advantage of having the high voltage corona-free connections between the test set and the pickup network, and the detector may be properly shielded to minimize stray pickup. A bushing located on top of the integrated unit provides a very convenient and corona-free location for connection to small test items. A single cabinet may be easier to handle within a laboratory than three separate interconnected units, since the various controls and displays are more conveniently grouped.

Equipment is usually interchangeable between manufacturers, although not generally recommended. Because of the high sensitivity of the detector at the lower ranges, it is sometimes necessary to resort to additional line filtering or screen-room techniques to completely eliminate or minimize stray noise. However, adequate sensitivity is generally available on the upper ranges so that the unit may be used in even a noisy location.

The use of high voltage direct current for corona testing is still in the experimental stage. Some work has been done, but to date there seems to be a lack of correlation with the results obtainable with alternating current. The standard corona detector-calibrator may be used in a direct current test but special techniques and circuitry are necessary in the pickup network and/or interconnections to avoid bypassing the corona through the test set's filter capacitors.

h. Calibration. Accepted calibration methods are described in ASTM Specification D-1868, "Method for Corona Measurement". A method of detection, measurement, and display is described in MIL-T-27, "Transformer and Inductor, Audio Power, and High Power Pulse, General Specification for."

89. ADVANTAGES AND DISADVANTAGES

a. Advantages.

(1) Works with nonmetallic materials.

(2) Provides good indications of voids and unbonded areas in reinforced plastics.

b. Disadvantages. The configuration of the electrodes and dielectric properties of the material are factors affecting resolution and sensitivity.

Section XV. LEAK TESTING

90. BACKGROUND

a. General. The word leak generally is used to refer to a hole or passage in the material being tested. The term leakage generally refers to the flow-rate of test medium through the hole or opening. In a specification, the phrase minimum detectable leak is generally used to describe the smallest size of hole that can be detected using a specified test method under specified conditions. Minimum detectable leakage refers to the least detectable fluid flow rate using a specified test method under specified conditions.

Discussions of the major types of leak testing generally include the following techniques:

(1) Measurement of change of system pressure with time.

(2) Use of tracer techniques and materials.

(3) Acoustical leak testing.

(4) Various special techniques such as passing light through pinhole-type leaks, and so forth.

Since there are many types of leak testing, the selection of one method over another must be evaluated relative to the type of test item involved and the sensitivity of results desired. Various types of leak tests and various aspects of leak testing are discussed in the following paragraphs.

b. Hydrostatic Testing. One of the most common methods of leak testing is the hydrostatic test. A simple example of this test is the one commonly used to detect leaks in automobile tire inner tubes. Leaks are located by immersing a pressurized inner tube in a tank of water and observing the surface of the immersed tube for bubbles which indicate holes in the tube. Welded pressure vessels and other items that can be closed off to form pressure vessels are often tested hydrostatically.

The test fluid may be inside or outside the test item for such tests. For some hydrostatic tests, colored dyes can be added to the water so that holes will be indicated more clearly. Although near-penetrating flaws may enlarge sufficiently to allow liquid seepage, only the flaws that completely penetrate the test item before test can generally be detected.

The presence of leaks can also be revealed by changes in the pressure of the liquid or gas being used as the pressurized medium. Water, oil, air or various special types of gases such as helium can be used as the pressurizing medium. It should be remembered, however, that the expansive force used in hydrostatic testing can be relatively great and can cause failure of the pressure vessel or can damage it. It is also possible to weaken the structure of the pressure vessel by over-pressurization.

When hydrostatic pressure is used, it should be applied gradually. Recommended test pressures are often indicated in specifications and codes. Procedures for hydrostatic testing are contained in the ASME Boiler and Pressure Vessel Code and in the American Standard Code for Pressure Piping and in applicable ASTM and military standardization documents.

One of the main reasons that water testing is not very sensitive is that leaks form comparatively large bubbles in a water medium. These bubbles take so long to form that they can easily be missed. Therefore, liquids having lower surface tension than water are often used. Such liquids include alcohol, acetone, or ether.

In observing a test item for bubbles, sufficient time should be allowed for the eyes to adapt to the surroundings. Good lighting is essential, and a dark test item surface may aid inspection. A small stream of bubbles may be more easily detectable from above than from the side. Sometimes a reading glass may be helpful in observing small bubbles on surfaces suspected of leaks. If large pressure vessels have to be hydrostatically tested, immersion may be impossible, but channels can often be built around areas suspected of containing leaks and the channels filled with alcohol or other suitable liquid.

c. Tracer Leak Testing. The following types of tracer leak tests may be used, depending on the test items and the sensitivity required.

(1) Bubble testing.

(2) Use of liquid penetrants.

(3) Mass spectrometer techniques.

(4) Radioactive materials.

(5) Halogen detection (by a change in positive ion emission and color change in gas discharge).

d. Bubble Tests. A pressure vessel can be covered with a soap solution and then pressurized so that leaks will cause bubbles to form and indicate the presence of holes. The bubble test is not generally considered to be highly sensitive when compared to many forms of gas testing (such as helium testing for example), but the bubble test can be made very sensitive by use of carefully controlled conditions and pressures.

The advantages of bubble testing are that it is cheap, can be done by inexperienced personnel, is rapid, gives accurate location of leak, and the whole test item can be inspected simultaneously. However, this technique cannot generally locate very small leaks. In some cases, leaks have been detectable in one direction only, and if this is inward the bubble technique would not reveal them. The ideal liquid for bubble testing would have a low surface tension and a low viscosity. The bubble size depends on the viscosity of the liquid, pressure used, and the diameter of leak. Many variations of the bubble technique are described in the literature.

e. Helium Testing (Mass Spectrometer Techniques). One of the more sensitive leak detection methods employs improved vacuum technique and a helium mass spectrometer leak detector. This type of detector is manufactured by several companies and can be used to detect the presence of less than one part of helium in 10,000 parts of air. The ultimate sensitivity of such devices on the market is usually listed on the basis of 100 percent tracer gas concentration, or on the amount of tracer leaking. In actual testing, the tracer gas concentration is normally well below the quoted rates for reasons of safety, etc. Therefore, the sensitivity of the leak detection method is also usually well below the quoted percentages.

A mass spectrometer is an instrument for separating or sorting atoms of different mass. A helium leak detector is a portable mass spectrometer specially designed to be highly sensitive to helium gas. Gas molecules entering the mass spectrometer are bombarded by electrons emitted by a heated filament. The resulting ion beam is accelerated in a narrow beam by means of an electrical field. The ions then pass between the pole-pieces of a permanent magnet. Here, the magnetic field deflects the ions in circular paths. The radius of path curvature depends on the mass of the ions. Therefore, ions having equal mass will all emerge from the magnetic field at a certain position. A helium leak detector is adjusted so that only helium ions are collected. The flow of helium ions to the collector constitutes a minute electrical current which can be detected, amplified, and used to activate an electrical meter and/or to control the pitch of an audio signal generator.

Prior to use of a sensitive test such as the helium test just described, it is generally a good idea to perform a simpler preliminary test, such as a hydrostatic or bubble test. This allows locating the large leaks before using the more sensitive method for the smaller ones. Also, the helium test is not amenable to detecting large leaks. Helium is usually used for leak detection because it is an inert gas and does not react with other gases and materials in the system. Helium is not present in any

significant quantity in the atmosphere, thus there is little interference in sensitive leak detection work. Helium has a light mass and therefore passes through small leaks more readily than heavier gases.

Four different techniques using a helium leak detector are described in the following paragraphs. These are the probe technique, sniffer technique, accumulation technique, and the pressurization technique.

In all these sensitive techniques, it is necessary to have clean, dry test items, since dirt, moisture, scale, and oil may easily seal comparatively large leaks. An idea of the importance of this is indicated by the fact that there is sufficient moisture in the human breath to plug a small leak.

(1) Probe Technique. In this technique, the test item is continuously evacuated by the auxiliary pump or pumps, and the internal atmosphere of the test item is continuously monitored with a leak detector. To detect leaks, a fine jet of helium, such as that obtained from a hypodermic needle, is passed over the exterior surface of an evacuated test item. Helium gas will be drawn into any opening through the walls of the test item and will register on the leak detector as a visible or audible indication. By using a small stream of helium, it is possible to locate precisely the position of an opening or openings in the test item and get a quantitative measure of its size. If the air surrounding the test item is somehow contaminated with a large amount of helium, the presence or position of a leak may not be distinguished because it will be masked by the high background indication. The size of leaks found using this technique can be determined by using a calibrated leak. Calibrated leaks can be obtained from commercial suppliers of helium leak detectors.

Sometimes it is desirable to determine only the presence of leaks or the total magnitude of all the leaks. In such a case, the test item can be surrounded with a helium atmosphere by putting it into some type of gastight chamber and monitoring the interior of the closed, evacuated chamber for helium content. A plastic bag often makes a satisfactory chamber.

(2) Sniffer Technique. Another technique consists of filling the test item with helium or a mixture of helium and air to a pressure greater than atmospheric. The surface of the test object is then scanned with a "sniffer" connected to the leak detector. Helium flowing out through any openings will be forced into the leak detector system by the sniffer. A variation of this technique is to fill the test item with helium at any pressure. The test item is then placed in a chamber connected to the leak detector and the chamber is partially evacuated. Helium will flow through any leaks into the evacuated chamber and then to the leak detector. This latter variation gives the overall leak rate of the test item. In using the sniffer (and in the other techniques), the presence of an excessive amount of helium in the atmosphere surrounding the test item may mask indications and positions of leaks.

(3) Accumulation Technique. In the accumulation technique, a static supply of helium is contained in the test item. The test item is placed in a glass chamber and the chamber evacuated. The helium leakage from the test item is allowed to accumulate for a given length of time. Then a gas sample from the accumulation chamber is analyzed for helium content.

(4) Pressurization Technique. The fourth technique, the pressurization technique, can be used to test items in which there is no way to attach the leak detector or a source of helium gas. In applying this technique, the item is first placed in a helium pressurizing vessel and exposed to a helium atmosphere. The pressure and the pressurization are not critical. After a suitable time, the test item is removed from the helium atmosphere and transferred to a second evacuated chamber which is connected to a vacuum pump and helium leak detector. Any helium which has leaked into the interior of the chamber will then leak out into the atmosphere being monitored and any leaks will then be detected. This technique has been used in the nuclear reactor field for detecting minute holes, cracks, and fissures in the cladding and end-weld closures.

f. Sonic or Acoustical Leak Detection. In this technique, the component or system is pressurized to its operating pressure or evacuated. The escaping gas or the flow of gas into the vessel produces a detectable sound. The background noise affects the size of the leak that can be found. The sensitivity of the technique can be increased by use of electronic devices.

g. Techniques Using Radioactive Material. A radioactive gas can be applied to the interior of the tank at differential pressure with respect to the internal pressure of the test item. The item is left in the gas for a sufficient period of time so that if the test item has a through hole, a sufficient amount of radioactive gas will accumulate in the vessel for detection. After removal from the tank, the item is cleaned to remove any radioactive contamination. It is then placed in front of a radiation detector. The counting rate determined by the radiation detection is directly proportional to the amount of radioactive gas in the item. The radioactive gas can be mixed with any suitable gas such as nitrogen. The sensitivity of the test can be varied by adjusting the gas pressure, the dilution factor, and the time in the pressure tank. It has been reported that this technique can detect, in small hermetically sealed parts, a leak of 1 standard cubic centimeter in 500 years. In theory, this limit can be extended by factors of 10 or more. A technique based on this principle has been used to test amplifiers for leak tightness.

Diversion of any liquid stream from one channel to another can be readily detected using radioactive material. Under the proper conditions such leaks can be measured quantitatively. Leakage between cross streams in a heat exchanger offers a good example of this technique. The radioactive material is injected in a short surge into the heating stream inlet. Radiation detectors are attached to the exit pipes of both the heating medium and the process streams. Indication of radiation by the detector on the process stream indicates a leak. Leak size is measured by the number of counts on this detector compared with that on the other detector.

Radioisotopes have also been used for testing leak tightness of nuclear plants. The technique includes filling the system with a radioisotope solution having an initial concentration of about 0.01 microcurie per milliliter of water. In using this technique, the welds, valve bonnets, and vent plugs are wrapped with absorbent tape. The pressure on the system is raised and held for 6 to 8 hours. Then the system is cycled several times, the system is depressurized, and the tapes are removed and "counted." From the counting rates obtained, small leaks can be located. In using radioactive material, care must be taken to prevent contamination of the test item and/or excessive exposure to personnel. The U.S. Atomic Energy Commission and the National Bureau of Standards have issued information on the handling of radioactive materials. (See the information regarding radioactive materials near the end of section VI in this chapter.)

h. Halogen Leak Test. In this technique, a halide detector is used. The detector instrument is fitted with a halide torch, a hose, and a probe-type inspirator.

The commercial halide torch used for leak testing makes use of a tank for gas and a brass plate. The gas is burned and heats the brass plate. In the presence of a halogen gas leak, the flame color changes because of the formation of copper halide.

The instrument available for performing halogen-type leak tests is a supersensitive instrument recommended for use with most gases that contain chlorine, fluorine, bromine, or iodine. These gases include Freon gas,* Genitron gas,† and the halogen gases. The Freon and Genitron families of gases include sulfur hexafluoride, trichloroethylene, and carbon tetrachloride. The halogen gases are chlorine, fluorine, bromine, and iodine. This instrument has been reported to be able to detect a leak so small that in a year only 0.01 oz. of Freon will pass through the opening. This corresponds to a halogen gas concentration of 1 part per million.

The basic principle used in this detector is use of a suction fan to draw a continuous sample of gas over the heated halogen-sensitive element (temperature approximately 1470° F). A precaution that must be observed in using this element is to keep the area in which the testing is being done free of vapors from halogen containing compounds. Otherwise, the presence of leaks may not be detectable because of background contamination.

91. CONCLUSIONS

Because the subject of leak testing is extremely broad and covers a variety of components and test items, pressure vessels, etc., only a brief coverage has been provided here.

*Freon is a registered trademark of Kinetic Chemical Division of E. I. du Pont de Nemours & Co.

†Genitron is a registered trademark of the General Chemical Division of the Allied Chemical and Dye Corporation.

Leak detection techniques have recently been evaluated for testing munitions and the results described in "Munitions Filling Development for New and Standard Agents", September 1966, available from the Chemical Process Laboratory Weapons Development and Engineering Laboratories, Edgewood Arsenal, Maryland.

92. SPECIFICATIONS

The expressions, "no leakage allowable" and "zero leakage," have been used in specifications and on drawings to specify the leakage limits of a particular system or component. This statement indicates a relative, rather than an absolute "zero," since "zero leakage," as an absolute term, would connote that there is no leakage present which could be detected by any method or instrument whatsoever. For this reason, the specifications and drawings should specify the method by which the system is to be tested. Specifications regarding leak testing might include the following or an equivalent statement:

> "Acceptable leakage rates for this test are confined to those obtained using the equipment and test methods specified herein. When 'no leakage allowed' is expressed or implied, this shall be construed to mean the result obtained under the circumstances of the tests per this specification only."

The engineering drawing should specify the: (1) method of test, (2) pressure, and (3) leakage rate per unit time.

PART TWO

SELECTION AND APPLICATION OF NDT METHODS

Section I. INTRODUCTION

1. INTERRELATED FACTORS

Nondestructive tests must be designed to insure validity, effectiveness, and reliability for each individual application. Also, they must be so scheduled in the life cycle of the materiel as to effect acceptance/rejection to established criteria at the earliest, most propitious moment. Since a highly complex relationship exists among the many factors involved, the specific objectives of each test must be thoroughly detailed and related directly to the particular problem being addressed. Each test design should be based on a thorough understanding of the nature and function of the item being tested, and on the conditions of its service. The guidelines set forth in this part of the handbook are intended to help in making a reasonable selection of the optimum test method for a given application from among the various candidate NDT methods, techniques, and procedures available. It should be emphasized that, since any test must be specifically suited to a given application, the information given here can only provide general guidance and criteria for use in the decision making process.

Section II. EFFECTIVENESS OF NDT

2. OBJECTIVES VERSUS COST

a. General. The objectives of NDT can be generally stated as: (1) to find and reject defective materials; and (2) to determine what caused the defects so that corrective action can be taken. The benefits involve safety or profits or both. Where nondestructive testing is performed for reasons of safety (as in most military and aerospace applications) it can save human life, and no further justification is usually required. In many fields where it is used, however, NDT not only produces safer operating conditions but it also helps reduce final costs, especially in production items.

b. Cost Effectiveness. In considering the use of various candidate NDT methods, the relative costs of the tests must usually be considered and weighed against the benefits which can be derived. Cost effectiveness analysis is a technique which can be used to assist in scientifically determining cost versus benefits for a given operation. This analysis technique essentially provides a systematic approach to the application of older, well known techniques; it does not eliminate the need for experience and good judgment but rather tends to reduce guesswork. The crux of cost-benefit analysis is to attempt to select a preferable alternative from a number of possible ways of achieving an objective.

Each of the alternative means has costs associated with it. Usually, a "model" or similar means of relating costs to benefits is required. These means can involve either relatively complex computations, or somewhat brief and generalized calculation.

The first step in such an exercise requires definition of objectives and the alternate ways of attaining these objectives. Then the relative costs of each alternate can be compared to assist in deciding on the preferred approach. Direct and other costs can generally be compared rather easily. However, cost effectiveness analyses attempt to relate intangibles to costs. Although intangibles such as safety and user satisfaction are not easy to put into absolute quantity form, such intangibles sometimes outweigh tangible benefits in NDT by such a large margin that they cannot be ignored. Analysis without them can often be meaningless and, therefore, they are assigned estimated values. With any cost analysis technique it is being increasingly recognized that the closer accept/reject testing can be brought to early material selection and processing, the more economical it is.

3. PLANNING A TEST

Some of the factors involved in comparative evaluation of test methods include the following:

(1) Research and development required.
(2) Equipment.
(3) Inspection training.
(4) Maintenance crew training.
(5) Labor.
(6) Rejected parts.
(7) Safety.
(8) Damage prevention.
(9) Efficient production.
(10) Efficient design.
(11) Salvage cost avoided.
(12) On-schedule development.

For the design engineer, NDT can mean achieving more efficient design and a broader choice of materials and by specifying appropriate nondestructive tests on the drawings, a designer can insure that defective parts will be identified and removed. For example, knowledge that tested and accepted parts will contain no harmful flaws allows specification and use of optimized mechanical and other materials properties with minimum added safety factors. It is recognized that if it were possible to establish nondestructive testing methods that could guarantee the quality of materials in new critical construction, and if the service behavior of materials and components could be continuously monitored, major improvements would be realized in design efficiency even with existing materials. NDT technology is constantly working toward these improvements.

Programs now evolving in NDT are shifting to a new area of planning where all of the factors, tangible and intangible, are being included in an organized fashion in the decision making process.

Section III. COMPARATIVE NDT

4. BACKGROUND

Nondestructive testing methods, in general, can be used for:

(1) evaluating a candidate material to be investigated for a new functional application or one newly developed for a special requirement; and

(2) flaw detection and analysis, where flaws are generally defined as voids, cracks, inclusions, and unbonded areas.

Recent years have shown significant developments in the use of NDT methods for evaluating candidate materials. In addition to evaluation by nondestructive testing, new materials can be subjected to destructive testing to provide a valuable combination of design information. The information given here, however, has been oriented primarily to flaw detection, for several reasons. One reason is that the scope of this presentation is necessarily limited. Another reason is that effective characterization of materials requires the concerted efforts of experienced materials scientists working with a variety of specialized laboratory equipment, methods, and techniques. Flaw detection, on the other hand, can often be performed by technicians trained in the use of relatively simple, commercially available test equipment. When this equipment is used in accordance with clearly written specifications and standards, reliable inspections can be performed. Also, the state-of-the-art for this type of testing is esbablished to a much greater degree than that for materials characterization, although both fields are advancing rapidly.

Before considering the relative merits of flaw detection, it should be noted here that product failures or malfunctions can be caused by many factors in addition to the existence of flaws. These factors include:

(1) improper matching of materials to service environment;

(2) inadequate inspection of raw materials and process control, and

(3) improper assembly of components.

If random failures are to be reduced, the cause or causes of each failure that does occur should be accurately determined. This will reveal if an assembly error, a material deficiency, or both caused the failure. If flaws caused the material deficiency, then the question of how to prevent recurrence of such flaws in future components must be addressed. The answer may be that NDT inspection should be performed at some point during the processing and

fabrication. The following paragraphs provide general information that can be used as guideline as to the relative merits of particular NDT methods (based on the type of materials and flaws that are to be investigated). As noted before, each application should be thoroughly analyzed for special circumstances and on the basis of final use.

5. TEST METHOD SELECTION

One of the first considerations in selecting an NDT method is the nature of the material to be inspected and its intended use. Metallic materials, for example, require much different considerations than plastics. Table I provides general guidelines for several NDT methods, shows when and where to use them, and details advantages and disadvantages inherent in each. Table II provides a general summary of testing methods for dielectric (nonconductive) materials. Table III provides a sample listing of factors to be considered in selecting NDT methods. Table IV provides more details regarding the type of flaws detected by the various NDT methods. Lastly, Table V contains a summary of the relative merits of 12 NDT methods. Again, it should be remembered that these tables are only to be used as general guidance.

6. TESTING SENSITIVITY AND LIMITATIONS

a. General. Special care and caution should be used in specifying the limits of sensitivity and accuracy required or expected in nondestructive tests. The sensitivity of every type of nondestructive test is limited. Sensitivity adequate for testing of one part may be totally inadequate for another test object, or for a more severe service condition on the same part. In general, more sensitive tests require more elaborate equipment and cost more. The cost of developing, proving, and applying a suitable nondestructive test must be considered in each application. Tests which cannot be applied economically in specific applications will usually be abandoned even when technically adequate, unless an extraordinary risk factor, such as affecting human life, is involved.

b. Interpretation Limitations. Even well-established NDT methods are subject to significant limitations. Radiography, for example, may reliably reveal porosity, shrinkage, inclusions, lack of penetration in welds, and similar defects; however, only in rare cases can the actual load for failure or the service life of an item be predicted quantitatively from X-ray examination. In fact, this would be difficult to do even if the parts were destructively sectioned for detailed internal visual examination.

Similarly, magnetic-particle inspection of ferrous materials can reveal surface cracks and defects reliably, but there are very few cases in which the fatigue strength or the number of load applications required to produce fatigue failure can be predicted from these test indications. Recognition that a surface crack or stress concentration may lead to premature failure under repeated loading is, however, generally sufficient basis for rejecting the material or part for such service.

TABLE I. GENERAL GUIDELINES FOR NONDESTRUCTIVE TESTING METHODS

Inspection Method	When to Use	Where to Use	Advantages	Limitations
VISUAL INSPECTION (Including use of Optical Aids)	Often can be used prior to use of other NDT Methods for surface flaws and to obtain information that can be used in subsequent NDT.	All materials should be subjected to some sort of visual testing during any phase of research/ development	Low in cost. Usually can be quickly performed. Results are often immediately available and can be photographed for record.	Limited to surface inspection only. Inspecting large surfaces may be tedious. Is somewhat inspector dependent.
PENETRANT	Locating surface cracks, porosity, laps, cold shuts, lack of weld bond, fatigue, and grinding cracks.	All metals, glass, and ceramics, castings, forgings, machined parts, and cutting tools; field inspections.	Simple to apply, portable, fast, low in cost; results easy to interpret; no elaborate setup required.	Limited to surface defects; surfaces must be clean.
MAGNETIC PARTICLE	Detecting surface or shallow subsurface flaws, cracks, porosity, nonmetallic inclusions, and weld defects.	Only for ferromagnetic materials; parts of any size, shape, composition, or heat treatment.	Economical, simple in principle, easy to perform; portable (for field testing); fast for production testing.	Material must be magnetic; demagnetizing after testing is required; power source needed; parts must be cleaned before finishing.
RADIOGRAPHY X-RAYS	Detecting internal flaws and defects; finding welding flaws, cracks, seams, porosity, holes, inclusions, lack of fusion; measuring variations in thickness.	Assemblies of electronic parts, castings, welded vessels; field testing of welds; corrosion surveys; components of nonmetallic materials.	Provides permanent record on film; works well on thin sections; high sensitivity; fluoroscopy techniques available; adjustable energy level.	High initial cost; power source required; radiation hazard, trained technicians needed.
GAMMA RAYS	Detecting internal flaws, cracks, seams, holes, inclusions, weld defects; measuring thickness variations.	Forgings, castings, tubular welded vessels; field testing welded pipe; corrosion surveys.	Detects variety of flaws; provides a permanent record; portable; low initial cost; source is small (good for inside shots); makes panoramic exposures.	One energy level per source; radiation hazard, trained technicians needed; source loses strength continuously.
ULTRASONIC PULSE ECHO	Finding internal defects, cracks, lack of bond, laminations, inclusions, porosity; determining grain structure and thicknesses.	All metals and hard nonmetallic materials; sheets tubing, rods, forgings, castings; field and production testing; in-service part testing; brazed and adhesive-bonded joints.	Fast, dependable, easy to operate; lends itself to automation; results of test immediately known; relatively portable, highly accurate, sensitive.	Requires contact or immersion of part, interpretation of readings requires training.
Resonance	Gaging thickness and locating laminar flaws.			

TABLE I. GENERAL GUIDELINES FOR NONDESTRUCTIVE TESTING METHODS (Continued)

Inspection Method	When to Use	Where to Use	Advantages	Limitations
EDDY CURRENT AND ELECTROMAGNETIC INDUCTION (CONDUCTIVITY)	Measuring variations in wall thickness of thin metals or coatings; detecting longitudinal seams or cracks in tubing; determining heat treatments and metal compositions for sorting.	Tubing and bar stock, parts of uniform geometry, flat stock, or sheets and wire.	High speed, noncontact, automatic equipment available.	False indications result from many variables; only good for conductive materials; limited depth of penetration.
MICROWAVES	Can be used to detect flaws such as laminations and voids in nonmetallic structures and products; monitor material moisture content, etc.	Filament wound rocket motor cases, insulation, solid propellant, and other dielectric materials, laminated products, etc.	Noncontact; no practical limitations to size of test item; ability to penetrate large masses of material.	Correlation of size of flaw and intensity of scattered energy is difficult; actual separation must be present before unbonded areas are detected.
THERMAL INSPECTION (INFRARED)	Can be used to detect overheating of electronic components, poor bondings of coatings; or porosity of coatings at low cost.	Filament wound rocket motor cases; internal inclusions and voids in many types of materials.	Noncontact, can be automated; can test moving surfaces; adaptable to oscilloscopes, C-scan recorders; etc. allows immediate observation.	Positioning of heat source, item, and detector may be critical; uniform initial heating of test item sometimes difficult.
LIQUID CRYSTAL INSPECTION (See Handbook Chapter 4, Section XII.)	Can be used to detect unbonded areas, cracks, and other flaws that interrupt heat flow. Also, can be used in leak testing.	Copper, aluminum, titanium, and boron compounds have been tested successfully. Many others possible.	Inexpensive; provides visual indications that can be immediately interpreted, recorded by photography.	Flaw depth is not indicated; method is relatively new and has not been fully explored.
KRYPTONATION	Can be used to measure surface temperatures, oxidation, friction, and corrosion of materials in service environment.	Practically any solid; over 50, including aluminum, copper, gold, silver, and boron composites have been tested.	Is convenient and accurate method of determining effects which formerly had to be detected by radiochemical analysis.	Involves radioactivity; is relatively safe to use however.
CORONA DISCHARGE	Can be used to detect flaws (voids) in dielectric material.	Practically any dielectric material can be tested.	Provides good method of indicating voids and unbonded areas in reinforced plastics; is safe and relatively inexpensive.	Configuration of electrodes and of the dielectric materials affect resolution and sensitivity.

TABLE II. NDT FOR INTERNAL FLAWS AND PHYSICAL CHARACTERISTICS IN DIELECTRIC MATERIALS

Note — The suitability of methods are applicable, but selection is influenced by changes in structure, geometry, composition, defect orientation, economy, etc.

Anomalies and Physical Properties*	Sonic	Ultrasonic		Radiographic	Gamma Radiation Detection	Beta Backscatter	Microwave	Thermal (Infrared)	Corona
		Contact	Immersed						
Reduced roving				X	X				
Irregular indexing of roving				X	X				
Roving knots				X	X				
Inclusions		X	X	X	X		X	X	
Voids	X	X	X	X	X		X	X	X
Porosity	X	X	X	X	X		X	X	X
Cracks	X	X	X	X	X		X	X	X
Excess resin and resin-rich areas			X	X	X	X	X		
Blocked resin voids		X	X	X	X		X	X	X
Thickness variations	X	X	X	X	X		X		
Roving end orientation				X					
Folded reinforcement				X					
Resin-poor areas			X	X	X	X	X		
Delamination	X	X	X				X	X	X
Reinforcement-to-resin ratio				X		X			
Degree of cure						X	X		
Density variations	X	X	X	X	X	X	X		

*Definitions of anomalies:

reduced roving—apparent looseness in the roving due to variation in roving tension.

irregular indexing of roving—any unintentional deviation in the roving pattern and spacing.

roving knot—a knot due to splice or tangle in the glass roving.

inclusion—particles of substances included in a laminate that seem foreign to its composition.

void—gas entrapment within and between the plies of reinforcement, usually spherical in shape.

porosity—presence of numerous visible pits or small craters in the surface of the laminate, with its width of approximately the same order of magnitude as its depth.

crack—actual separation of the material; may be visible on opposite surface of the plastic or extend through the thickness.

excess resin and resin-rich area—accumulation of resin in a localized area in the laminate.

thickness variation—differences or variations in cross section of the material.

roving end orientation—angle between terminated roving and direction of wrap.

folded reinforcement—reinforcement that is doubled over on itself.

resin-poor area—area of insufficient resin in a localized area in the laminate.

delamination—separation of the layers of material in a laminate.

reinforcement-to-resin ratio—the ratio of the amount of reinforcement to the amount of resin (by weight).

degree of cure—the degree of change in the properties of a polymeric system into a final, more stable, usable condition by the use of heat, radiation, or reaction with chemical additives.

density variation—any variation in the laminate in weight per unit volume.

TABLE III. COMPARISON OF SEVERAL COMMON NDT METHODS

	Eddy Current	Gamma Rays	X-Rays (Film and Fluoroscopy)	Ultrasonic-Sonic (Pulse-Echo and Resonance)	Magnetic Particle	Penetrants	Thermal
When to Use	1. Surface and subsurface cracks and seams. 2. Alloy. 3. Heat treatment. 4. Wall thickness. 5. Coating thickness. 6. Crack depth.	Internal flaws and variations, porosity, inclusions, cracks, lack of fusion, geometry variations.	Internal flaws and variations; porosity, inclusions, cracks, lack of fusion, geometry variations.	Internal flaws and variations; cracks, lack of fusion, porosity, inclusions, lack of bond.	Surface and slightly subsurface flaws.	Defects open to surface of parts.	Lack of bond.
Where to Use	1. Tubing. 2. Wire. 3. Ball bearings. 4. "Spot checks" types of surfaces.	Usually where X-ray machines are not suitable because tubes cannot be placed in parts with small openings and/or power source not available.	1. Castings. 2. Electrical Assemblies. 3. Welds. 4. Small, thin, complex wrought products. 5. Nonmetallics.	1. Wrought metals. 2. Welds. 3. Brazed joints. 4. Adhesive-bonded joints. 5. Nonmetallics. 6. In-service parts.	Ferromagnetic materials.	All parts with nonabsorbing surfaces. Note: Bleedout from porous surfaces can mask indications from flaws.	1. Brazed joints. 2. Adhesive bonded joints with metal skins. 3. Metallic platings or coatings.
Why to Use	1. No special operator skills required. 2. High speed, low cost. 3. Symmetrical parts; may be automated with permanent records. 4. No coupling material or contact between probe and part.	1. Low initial cost. 2. Permanent records; film. 3. Small sources can be placed in parts with small openings.	1. Permanent records; film. 2. Adjustable energy levels. 3. High sensitivity to to density changes. 4. No couplant required. 5. Geometry variations do not effect direction of X-ray beam.	1. Most sensitive to cracks. 2. Test results known immediately. 3. Operation can be made simple with automation and permanent records. 4. Portable. 5. Great penetration.	1. Advantage over permanent in that it indicates subsurface flaws; particularly inclusions. 2. Relatively fast and low in cost. 3. May be portable.	1. Low cost. 2. Portable. 3. Indications may be further examined visually. 4. Results easily interpreted.	1. Very low initial cost. 2. Can be readily applied to surfaces which may be difficult to inspect by other methods. 3. No special operator skills.
Limitations	1. Conductive materials. 2. Depth of penetration; thin walls only. 3. Masked or false indications caused by sensitivity to variations, such as part geometry.	1. One energy level per source. 2. Source decay. 3. Radiation hazard. 4. Trained operators. 5. Unsharpness of image.	1. High initial costs. 2. Orientation of linear defects in part may not be favorable. 3. Radiation hazard. 4. Depth of defect not indicated. 5. Sensitivity decreases with increase in thickness of part.	1. Liquid couplant required. 2. Small, thin, complex parts may be difficult. 3. Trained operators for manual inspection.	1. Alignment of magnetic field may be difficult in some complex shapes. 2. Demagnetization of parts required after tests. 3. Parts must be cleaned after inspection.	1. Surface films, such as coatings, scale, and smeared metal may prevent detection of flaws. 2. Parts must be cleaned after inspection.	1. Thin-walled surfaces only. 2. Critical time-temperature relationship. 3. Image sensitivity affected by humidity.

TABLE IV. SUMMARY OF COMMON NDT METHODS FOR METALS

	Liquid Penetrant Testing	Magnetic Particle Testing	Radiographic Testing	Eddy Current Testing	Ultrasonic Testing
DEFINITION	Uses a penetrating liquid to seep into a surface flaw thus providing a visible indication.	Uses electrical current to create a magnetic field in a test item while magnetic particles indicate where the field is broken by a flaw	Uses electromagnetic rays (X-Rays and Gamma Rays) to penetrate material, recording flaws on film.	Uses an electrical current in a coil to induce eddy currents into a test item. Indicators reveal flaws that alter the path of the induced currents.	Uses ultrasound to penetrate material, indicating flaws on an oscilloscope screen
USES	Used on metal, glass, ceramics to locate surface flaws. Simple to use and does not require elaborate equipment.	Used on metal which can be magnetised (ferromagnetic) to detect surface or subsurface flaws. Simple to use and equipment is portable for field testing.	Used on any metal stock or articles, as well as a variety of other materials to detect (and record on film) surface or subsurface flaws. Film provides a permanent record of the flaws.	Used on metals to detect surface and subsurface flaws, hardness, and thickness. Plating coating (nonmetallic), and sheet thickness measurements.	Used on metal, ceramics, plastics, etc., to detect surface and subsurface flaws. When automated, indications are recorded on paper, providing a permanent record. Also measures material thickness
LIMITATIONS	Does not detect flaws beneath the surface of a test item.	Cannot be used on metal which cannot be magnetized. Requires electrical power.	High initial cost. Requires electrical power source. Potential safety hazard to personnel.	Inspection depth limited to less than one inch. Does not give physical shape of flaws	Moderately high initial cost. Requires electrical power source. Interpretation of test results requires high-trained personnel.

TABLE V. RELATIVE MERITS OF NDT METHODS

VISUAL
Generally valuable for checking surfaces for flaws and dimensional characteristics. Should be used when test item surfaces are accessible — both as a separate NDT method and to provide information prior to performing other NDT checks.
LIQUID PENETRANT
Can be used to test practically any material regardless of physical characteristics for surface flaws only. Surface must be clean and free of contaminants. Sometimes used as a leak test (opposite side of test material is checked for bleed-through of penetrant). Geometry of test item is relatively unimportant. Cannot be used to test porous surfaces. Penetrant removal after test may be a problem.
MAGNETIC PARTICLE
Can be used only on ferromagnetic materials (and sometimes to detect ferromagnetic inclusions in non-ferromagnetic materials). Detects inclusions and segregations as well as cracks and voids. Detects surface flaws and those just below the surface. A thin coating (such as cadmium) does not greatly affect item inspectability. Flaw contamination does not greatly affect results (as it does with penetrants, for example). Complex-shaped test items can cause difficulties. Item must be demagnetized after test.
ULTRASONIC
Offers valuable inspection means for testing smooth-surfaced, fine-grained items, especially steel and aluminum products. Considerable thicknesses can be tested from any accessible surface, but couplants are required between the test item and test instrument transducer. Items can be tested with oil-type couplants or immersed in water couplant. Flaw location and depth can be approximately determined. Automation is common. Complex-shaped test items are sometimes impossible to test adequately, as are rough surfaces, large-grained

TABLE V. RELATIVE MERITS OF NDT METHODS (Continued)

ULTRASONIC (cont.)
materials, and fiber reinforced composites. Some items must be tested from various directions to insure that flaws oriented in all directions are detected. Principal advantages are that fine cracks a considerable distance from the transducer can be detected and results are immediately available.
X- AND GAMMA-FILM DETECTION
Old, widely used, and respected method. The shape of the flaw can be viewed and approximate depth can be determined with special techniques. Films are relatively expensive and processing can require considerable time. Almost any material can be radiographed. Special precautions are necessary to avoid hazards from radiation. Often used to check or confirm results of other tests. Detects internal flaws in items not excessively thick.
FLUOROSCOPIC
Capabilities are similar to X- and gamma-ray radiography, except that contrast is not as good with fluoroscopy and thicknesses of inspectable test items are not as great. The results of fluoroscopy are viewed on a fluorescent screen and are, therefore, immediately available. Faster testing, and testing of moving items are possible (which is sometimes a considerable advantage since it allows orienting test items to reveal flaws at advantageous viewing angles). Fluoroscopy is sometimes used as a "gross" inspection technique followed by film radiography for better resolution of indicated flaws.
EDDY CURRENT
Can be used to inspect "conducting" material only. Nonmetallic contaminants on test item do not affect results significantly. Testing speeds can be high because of the inherently high exciting frequencies used. Capable of inspecting large quantities rapidly and is easily adapted to automation. The method is sensitive to geometry and limited to simple shapes unless complicated scanning systems are designed and employed. Encircling coils may be used to inspect complex

TABLE V. RELATIVE MERITS OF NDT METHODS (Continued)

EDDY CURRENT (cont.)	
shapes but this does not allow pinpointing flaw locations. When used for flaw detection, other effects such as variations in permeability sometimes cannot be eliminated from the display or readout and, hence, confuse results. Direct contact between test item and test instrument probe is not required.	
ELECTRICAL CONDUCTIVITY	
Can be used in production capacity to determine segregation conditions of metals and materials being produced. Is especially valuable in rapidly sorting mixed scrap materials and determining the degree of purity of metals. Hardness measurements can be made much more rapidly than with standard Brinell test for example. Austentic steels (stainless steels), copper, aluminum, and their alloys can be sorted as well as graphite or carbon. More recently, titanium alloys have been hardness tested by the conductivity method. Overheated parts and parts quenched at too high a temperature can be eliminated from production areas as a result of their low conductivity. Can be used for testing the uniformity of hardness on semi-finished parts (rods, sheets, extruded shapes, and tubes). Is sensitive to a large variety of test item conditions and tests must be carefully designed and planned to produce only desired information.	
MICROWAVES	
Can be used to penetrate most nonmetallic opaque materials and structures where they interfere and scatter from internal flaws so that the presence of these flaws can be indicated on an X-Y recorder. Microwave reflectometer techniques have been used to detect unbonded areas in such diverse products as glass-fiber, resin impregnated honeycomb panels and automobile brake shoes. Moisture sensing can also be performed with microwaves. Orientation of fibers in fiber reinforced materials can also be determined. Microwaves have the ability to pass through large thicknesses of non-metallic materials (several feet of plastic for example). The method is still being developed, however, and no widely accepted standard test procedures are available.	

TABLE V. RELATIVE MERITS OF NDT METHODS (Continued)

INFRARED	
Can be performed using a non-contact, radiometer-equipped camera system to scan radiant energy patterns emitted from the surface of a heated test item to indicate flaw locations by observing differences in heat patterns from test item areas. Has been suggested as method to test the surface of test items in environmental chambers to observe the effects of heat on various components and areas. Practically all materials can be tested using this method. Flaws, in welds are detectable, for example: Can be used to scan large test items for unbonded areas, porosity, inclusions, etc. Can produce permanent results and is adaptable to automation. However, some disadvantages exist and method is still under development.	
LIQUID CRYSTALS	
Can be used advantageously in leak testing as well as flaw detection. Relatively new NDT technique is finding wider range of applications and is still under development. Can be used on practically any material by applying the thermally sensitive coating (generally cholesteric crystals) and observing (or recording by photography) color changes in the coating -- indicating thermal gradients and hence flaws or leaks. The thermal variations can be observed directly on the test item surface. Liquid crystals can be coated on local areas suspected of leaks, flaws, etc., or coated over the entire surface of test items. Can be used as "check" on leaks or flaws indicated by penetrant testing for example. Available in several forms and can be "encapsulated" for special applications. Can also be used to detect bond separation. Large or small areas can be tested with relative ease and complex-shaped test items offers no particular problems. The method is relatively new, and development is continuing. Flaw depth is not indicated.	
KRYPTONATION	
Can be incorporated into the matrix of solids to form the basis of: (1) peak surface temperature the test item has reached in service or testing; (2) oxidation; (3) surface wear; and (4) corrosion. These effects are measured by monitoring rate of release of radioactive krypton-85 from the previously kryptonated test items and, hence,	

TABLE V. RELATIVE MERITS OF NDT METHODS (Continued)

KRYPTONATION (cont.)
there is no need for destructive wet chemical analysis. A unique advantage is that it allows monitoring the effects mentioned while the test item is in service environment and where NDT would otherwise be impossible. This method is still under investigation and development.
CORONA DISCHARGE NDT
Can be used to test non-metallic materials to provide good indications of voids and unbonded areas in reinforced plastics. Readout may be on a strip chart recorder or displayed on an oscilloscope. Is especially valuable in checking various insulation and dielectric materials for voids. Method is still under development, especially in flaw detection area.

c. Geometric Limitations. In designing, specifying, or applying nondestructive tests, it is important to recognize certain geometric limitations in their scope and sensitivity. Some test methods are specifically limited to test objects with reasonably flat or parallel surfaces, or even to constant thickness sections. Ultrasonic-resonance thickness gaging is naturally limited to walls or plates with nearly parallel surfaces, in order that echoes may return to the sensing probe.

A few types of nondestructive tests are applicable only to items of exactly identical geometry. Some electromagnetic-induction, or eddy current, test devices can only detect flaws in symmetrical rods or bars of given shape and diameter.

d. Accessibility Limitations. Some test methods require access to opposite sides of the test item. In many tests, the source of the probing medium is located on one side of the test object and the detector on the opposite side, like the X-ray tube and the film in radiography.

Other methods are designed for (or can be modified for) use as one-side tests. For example, magnetic-particle inspection, ultrasonic-reflection techniques, and all liquid-penetrant tests may be used in this way.

e. Size and Shape Limitations. Some test methods may be applied to parts of almost any shape or size, and portable apparatus is available to examine large, fixed structures in the field. Other tests involve the use of massive testing units on fixed foundations with limited maneuverability within a confined testing area. Their use is limited to test objects which can be brought into the test area and positioned properly relative to the test apparatus.

Other tests have definite thickness limits. Beta-ray thickness gages, for example, can penetrate only very thin layers of most materials. Contact probe ultrasonic-pulse-reflection tests require sufficient material thickness above the flaws to permit the pulse from the source to attenuate before the defect signal returns.

f. Material Limitations. A few tests are limited to certain kinds of materials. Magnetic-particle tests, for example, are useful only with ferromagnetic materials. They cannot be used for light alloys or for the nonmagnetic stainless steel alloys.

7. SCHEDULING TESTS FOR MAXIMUM EFFECTIVENESS

The scheduling of nondestructive tests often has a critical influence upon their cost, effectiveness, and overall value. In production, it often proves most effective to apply nondestructive tests at the earliest possible steps in which the potential flaws are present and detectable. In this way, potential rejects are eliminated before any further fabrication or handling costs are incurred.

a. Raw Materials. It is frequently good practice to inspect raw materials before or as they enter the plant. Such inspection may be done by the supplier, an independent laboratory, or in the receiving inspection department. In this way, defective raw materials cannot enter the production or assembly areas of the plant where they might be accidentally mixed into good production lots.

In some cases, raw-material flaws may not be accessible for detection until some processing steps have been completed. In these cases inspection normally should directly follow the process step which makes their detection feasible.

b. Processed Materials. Where processing steps may introduce defects, inspection can best be applied as soon after processing as feasible. Where fabrication is costly, it is dangerous and uneconomical to leave all inspection to the final, finished-product stage. Here, each rejected unit is most expensive. Any failure to detect the rejectable defects may also send a defective unit into service to cause a premature failure, which may be far more costly.

c. Materials in Service. The optimum interval between nondestructive tests for damage in service varies with the conditions of service or with the types of defects. Obviously, this period should be short enough so that defects not detectible at the preceding inspection do not have time to propagate to failure between inspections. In many types of service there are natural locations or periods of time at which inspection can be made most economically. Good engineering judgment based on extensive experience is usually required for establishing an optimum inspection schedule.

d. Number of Different Tests. The question of how many different nondestructive tests to apply at a particular time or at a specific stage of service or production is also usually difficult to answer. If specific nondestructive tests for each of the potential causes of failure are combined into large and complex nondestructive test operations, the costs can be unreasonably high. Consequently, the designer, materials or process engineer, and the service engineer should determine which properties are of practical limiting importance in production or service. Only those properties which cannot be more economically or reliably controlled through other methods of process control or inspection should be reserved for nondestructive testing.

8. NOTES ON THE TEST SELECTION CHARTS

a. Purpose of Charts. In the vast scope of nondestructive testing, there are numerous basic methods in common use. These methods are applied to all kinds and forms of materials (cast, forged, etc.), sizes, shapes, and fastenings (welds, bolts, etc.). With each new nondestructive testing problem, it may be uncertain which of the methods and techniques can possibly find the type of defect important in the particular product to be tested. Analysis programs must then be conducted.

b. Limitations of Charts. The test method suitability and comparison charts are designed to be a handy guide or first check list of the capabilities of the various test methods. The charts are indicative, not conclusive. They are "averages" of expert opinion. They are based on the supposition that the particular test method is applied to any specific defect-detection problem with:

(1) adequate equipment;

(2) high grade materials;

(3) qualified production-testing personnel; and

(4) normal production-testing conditions.

c. Use of Charts and Guides. As stated, charts and guides are indicative but not conclusive. They are intended as a general guide to the potential use of each method and technique. It is expected that the user will usually have a problem of locating some specific type of defect in a specific kind of material. The charts are designed to aid him in determining what standard nondestructive tests may be potentially considered as having the ability to locate that defect.

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